

Efficient and Privacy-Preserving Infection Control System for Covid-19-Like Pandemics using Blockchain

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Abstract—Contact tracing is a very effective way to control the COVID-19-like pandemics. It aims to identify individuals who closely contacted an infected person during the incubation period of the virus and notify them to quarantine. However, the existing systems suffer from privacy, security, and efficiency issues. To address these limitations, in this paper, we propose an efficient and privacy-preserving Blockchain-based infection control system. Instead of depending on a single authority to run the system, a group of health authorities, that form a consortium Blockchain, run our system. Using Blockchain technology not only secures our system against single point of failure and denial of service attacks, but also brings transparency because all transactions can be validated by different parties. Although contact tracing is important, it is not enough to effectively control an infection. Thus, unlike most of the existing systems that focus only on contact tracing, our system consists of three integrated subsystems, including contact tracing, public places access control, and safe-places recommendation. The access control subsystem prevents infected people from visiting public places to prevent spreading the virus, and the recommendation subsystem categorizes zones based on the infection level so that people can avoid visiting contaminated zones. Our analysis demonstrates that our system is secure and preserves the privacy of the users against identification, social graph disclosure, and tracking attacks, while thwarting false reporting (or panic) attacks. Moreover, our extensive performance evaluations demonstrate the scalability of our system (which is desirable in pandemics) due to its low communication, computation, and storage overheads.

Index Terms—Privacy preservation, security, contact tracing, infection control, and COVID-19.

I. INTRODUCTION

COVID-19 virus has spread quickly to all countries in the world causing a large number of infected people and deaths. By January 2021, the number of infected cases worldwide has reached 86+ million cases, and the number of deaths is around 2 million [1]. The devastating impacts of the COVID-19 pandemic on health, society, and world economy exceeded any other crisis since World War II, as the Secretary-General of the United Nations announced. For the impact on the healthcare sector, COVID-19 patients overwhelmed

the hospitals and doctors had to make tough life and death decisions in some countries [2]. For the impact on society, the panic and the lockdown caused by COVID-19 outbreak resulted in adverse mental health consequences and common psychological reactions such as anxiety, depression, stress, and lack of sleep [3]. For the impact on the economy, COVID-19 disrupted many industries and sectors due to sickening workers and the restrictive measures imposed by the governments on the travel and the gathering of the people [4]. For instance, the travel industry and tourism suffered from hefty losses because many countries suspended all air flights and closed their airports. The aviation industry lost 113 billion dollars in total [4].

The high infection level of the virus and the severe symptoms it may cause forced many countries worldwide to impose harsh measures to slow down the spread of the virus. Some of these measures include isolation of infected people, enforcing partial/complete lockdown of cities and provinces [5], promoting social-distancing [6], preventing large gatherings, and advising citizens to wear masks. However, an individual may be contagious but does not show any symptoms during the incubation period of the virus, which is 14 days in case of COVID-19. During this period, he may interact with people and pass the virus to them. Therefore, contact tracing is one of the most effective ways to control COVID-19-like pandemics [7]. It aims to identify individuals who closely contacted an infected individual during the incubation period of the virus. The health authorities in Germany performed manual contact tracing in an attempt to slow down the spread of COVID-19, which showed success in the first few weeks, but manual tracing was not practical when the number of cases increased [8]. This indicates that contact tracing can be effective to contain COVID-19 like pandemics, but it needs to be automated to deal with the large number of infected cases.

Multiple automated contact tracing systems [9]–[18] have been developed by governmental and private institutions. These systems depend on exchanging messages between the users' smartphones when they encounter each other as a proof of contact. Then, if a user is tested positive for COVID-19, the messages collected by the user during the incubation period are used to identify the close contacts, and thus these people are notified to quarantine to prevent the spread of the virus. However, the existing contact tracing systems suffer from privacy, security, and efficiency issues.

In terms of privacy, the existing systems are vulnerable to one or multiple privacy attacks such as identification, tracking, and social graph disclosure. In identification attack,

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an adversary tries to identify a particular person from his messages transmitted in the system and learn his COVID-19 status, i.e., whether he/she is infected with COVID-19. In tracking attack, an adversary tries to learn the locations visited by a person using the messages collected by the system. In social graph disclosure attack, an adversary tries to learn social relationships, i.e., the users who met the infected user. *Without privacy preservation, the system can be misused to spy on the people* to learn their visited locations and social activities, which may discourage the users to use the system. In terms of security, most of the existing systems [9]–[13], [17] are based on centralized architecture which is vulnerable to a single point of failure problem and denial of service (DoS) attack, and the lack of transparency. Furthermore, some of the existing systems suffer from false reporting (or panic) attack, where an adversary can deceive the system to incorrectly classify individuals as close contacts. In terms of efficiency, the existing systems suffer from large communication and computation overheads and inefficient storage usage, especially when the number of users increases.

To address the above limitations, in this paper, we propose an efficient and privacy-preserving Blockchain-based infection control system. Instead of depending on a centralized authority to run the system, a group of health authorities, that form a consortium Blockchain, runs our system. Using Blockchain technology not only secures our system against the problems caused by the centralized architecture, but also brings transparency because all transactions can be validated by different parties. Although contact tracing is important, it is not enough to effectively control the infection. Thus, unlike most of the existing systems [9]–[15], [17], [18] that focus only on contact tracing, our system consists of three integrated subsystems, including *contact tracing*, *public places access control*, and *safe-places recommendation*.

The *contact tracing* subsystem is responsible for identifying the individuals who closely contacted an infected person during the incubation period of the virus and notifying them to quarantine. The *access control* subsystem is responsible for providing a digital pass to users to prevent infected users from accessing public places, such as restaurants, institutions, libraries,...etc., to prevent spreading the virus. The *recommendation* subsystem is responsible for categorizing zones based on their infection level. Users can use this information to avoid visiting contaminated zones to prevent spreading the virus. Our security and privacy analysis demonstrate that our system is secure and preserves the privacy of the users against identification, social graph disclosure, and tracking attacks, while thwarting the false reporting attack. Moreover, our extensive performance evaluations demonstrate the scalability of our system due to its low communication, computation, and storage overheads.

Our main contributions can be summarized as follows:

- Our system consists of three integrated subsystems including *contact tracing*, *public places access control*, and *safe-places recommendation*, while most of the existing systems focus only on contact tracing which is not enough to control the infection.

- Our system is secure against multiple privacy attacks including, identification, social graph disclosure, and tracking attacks. Moreover, it is secure against false reporting (or panic) attack.
- Our system is scalable because it is efficient in terms of computation and communication, and also requires low storage space.

The remainder of this paper is organized as follows. Section II covers preliminaries and essential background. The network and threat models and design objectives are explained in section III. The details of the proposed infection control system are presented in section IV. The security and privacy analysis are provided in section V, and the performance evaluations are provided in section VI. Section VII discusses the related works. Finally, conclusions are drawn in section VIII.

II. PRELIMINARIES

In this section, we present the necessary background on Blockchain, bilinear pairing, and Bloom filter.

A. Blockchain

Blockchain is a distributed ledger that consists of blocks of data chained together using cryptographic hash functions. The content of the ledger is shared by the entities of a peer-to-peer network and they agree on the content of the ledger using a consensus algorithm [19]. Blockchain allows entities that do not trust each other to transact without the reliance on a centralized trusted entity [19]. Blockchain was initially proposed as an enabling technology for cryptocurrencies, but later it has been used to secure many other applications and build secure systems [19]. The decentralized network architecture of Blockchain secures systems against the single point of failure problem and the DoS attacks. Moreover, Blockchain provides immutability in the sense that once a data is written in the ledger, it is impossible to maliciously modify it because this requires controlling the majority of the network nodes, which is impossible to achieve. Blockchain also provides transparency because all the transactions are validated by all the network nodes [20].

There are two types of Blockchains, namely permissionless and permissioned [21]. Permissionless Blockchain is a public Blockchain, where any entity can join the network and all the network entities can read/write from/on the Blockchain [21]. On the other hand, in permissioned Blockchain, the network access is limited only to authorized entities. One type of permissioned Blockchains is the consortium Blockchain in which only a group of entities have the right to write on the Blockchain and all entities have the right to read from the Blockchain [21]. Consortium Blockchain is appropriate for our system, where only the health authorities are able to do COVID-19 tests and they should be able to update the status of the users on the Blockchain, while, the users need only to check their status by reading data from the Blockchain.

The group of entities that have the right to write on the Blockchain are called validators. To maintain a unified ledger, validators have to agree on the content of the ledger. This is done through using consensus algorithms. The existing

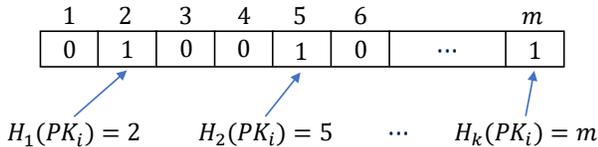


Fig. 1: An illustration for the Bloom filter.

consensus algorithms can be classified into proof-based and voting-based [22]. One type of voting-based algorithms is Raft in which one validator is elected every period as a leader to add a new block to the ledger [23]. In our system, we use the Raft consensus algorithm because it is more efficient than proof-based consensus algorithms such as proof of work or proof of stake. In Raft, one validator acts as a leader and the other validators act as followers. Every election period, any follower who wants to be a leader becomes a candidate and collects votes from the followers. Finally, the candidate who collects the majority of votes becomes the leader. It is noteworthy to mention that Raft is used in several applications such as Quorum Blockchain of JPMorgan system [24]. For more details about Blockchains and consensus algorithms, we refer to [21]–[23], [25].

B. Bilinear Pairing

Let G be a cyclic additive group of prime order q and has a generator P , and G_T be a cyclic multiplicative group of the same prime order q . Let $e: G \times G \rightarrow G_T$ be a bilinear map with the following properties.

- $e(aP, bQ) = e(P, Q)^{ab}$, where $P, Q \in G$, and $a, b \in \mathbb{Z}_q$.
- $e(P + P_1, Q) = e(P, Q)e(P_1, Q)$, where $P, P_1, Q \in G$.
- There exists $P, Q \in G$ such that $e(P, Q) \neq 1$.
- There is an efficient algorithm to compute $e(P, Q)$ for all $P, Q \in G$.

C. Bloom Filter

Bloom filter is an efficient data structure that has been used in different applications [26]. In particular, the filter is a bit vector used to store a list of elements in an efficient way. Fig. 1 illustrates the basic idea of Bloom filter. The Bloom filter in Fig. 1 consists of m bits that are initially set to zeros [26]. To store an element (e.g., PK_i) in the filter, k different hash functions (H_1, H_2, \dots, H_k) are used to calculate the k hash values of the element. The output of each hash function gives a number between 1 and m [27], i.e., points at a bit position in the vector. To add an element to the list, the bits the hash functions point at are set to ones. To check if an element is stored in the filter, the k hash values of this element are calculated. If all the k locations of the hash values store ones, the element is likely stored in the filter; otherwise, the element is not definitely stored in the filter. It is possible that an element is not stored in the filter but all the locations resulted from the k hash functions are ones because by coincidence the ones in the k locations come from other elements, and this case is called false positive. The probability of false positive is calculated as follows [28].

$$(1 - (1 - 1/m)^{kn})^k \quad (1)$$

where n is the number of elements stored in the filter. By properly selecting the parameters of this equation, the false positive probability can be small.

III. NETWORK/THREAT MODELS AND DESIGN GOALS

In this section, we explain the network and threat models considered in this paper and the design goals of our system.

A. Network Model

As illustrated in Fig. 2, the network model considered in this paper has five main entities, including a *key distribution center (KDC)*, a *consortium Blockchain*, *health authorities*, *users*, and *public places*. The role of each of these entities and the type of the communications among them are as follows.

KDC. The KDC is responsible for initializing the entire system. This includes the registration of users, health authorities, and places, and also the generation and renewal of their cryptographic keys. To preserve privacy, each user receives anonymous credentials that are used only for a short time. Moreover, as shown in the figure, the health authorities need to communicate with the KDC, so that it does not renew the anonymous credentials of the infected users.

Consortium Blockchain. Consortium Blockchain is used to run our system in a distributed manner without the need to trust a centralized entity. The Blockchain validators are the health authorities, and they are responsible for creating and updating two ledgers for users' COVID-19 status and zones' infection levels.

Health authorities. Health authorities in our system could be hospitals, clinics, laboratories, testing centers, etc. They are responsible for conducting COVID-19 tests, collecting the proof-of-contact messages collected by the infected users during the incubation period of the virus (the past 14 days), and notifying the close-contact users. They are also responsible for creating and updating two lists for the public keys of the infected users and the probably infected (suspected) users, and posting them on the Blockchain. Moreover, the health authorities need to notify the KDC with keys of infected and suspected users to stop renewing their keys until the KDC is notified by the health authorities that the users are tested negative for COVID-19. Finally, the health authorities are responsible for categorizing zones based on their infection levels and post this information on the Blockchain.

Users. The users of our system use their smartphones equipped with Bluetooth technology to exchange proof-of-contact messages when their phones are in close proximity. These messages are stored in the users' smartphones for the incubation period of COVID-19. If users get infected, they upload the proof-of-contact messages to the health authority. Users query the Blockchain to know whether they contacted an infected person, and also to learn the infection level of the zones before visiting them.

Public places. Public places in our system could be restaurants, libraries, companies, theatres, shopping centers, educational institutes, etc. At the entrance of these places, the infection status of each user is checked by querying the Blockchain before allowing them to access the places.

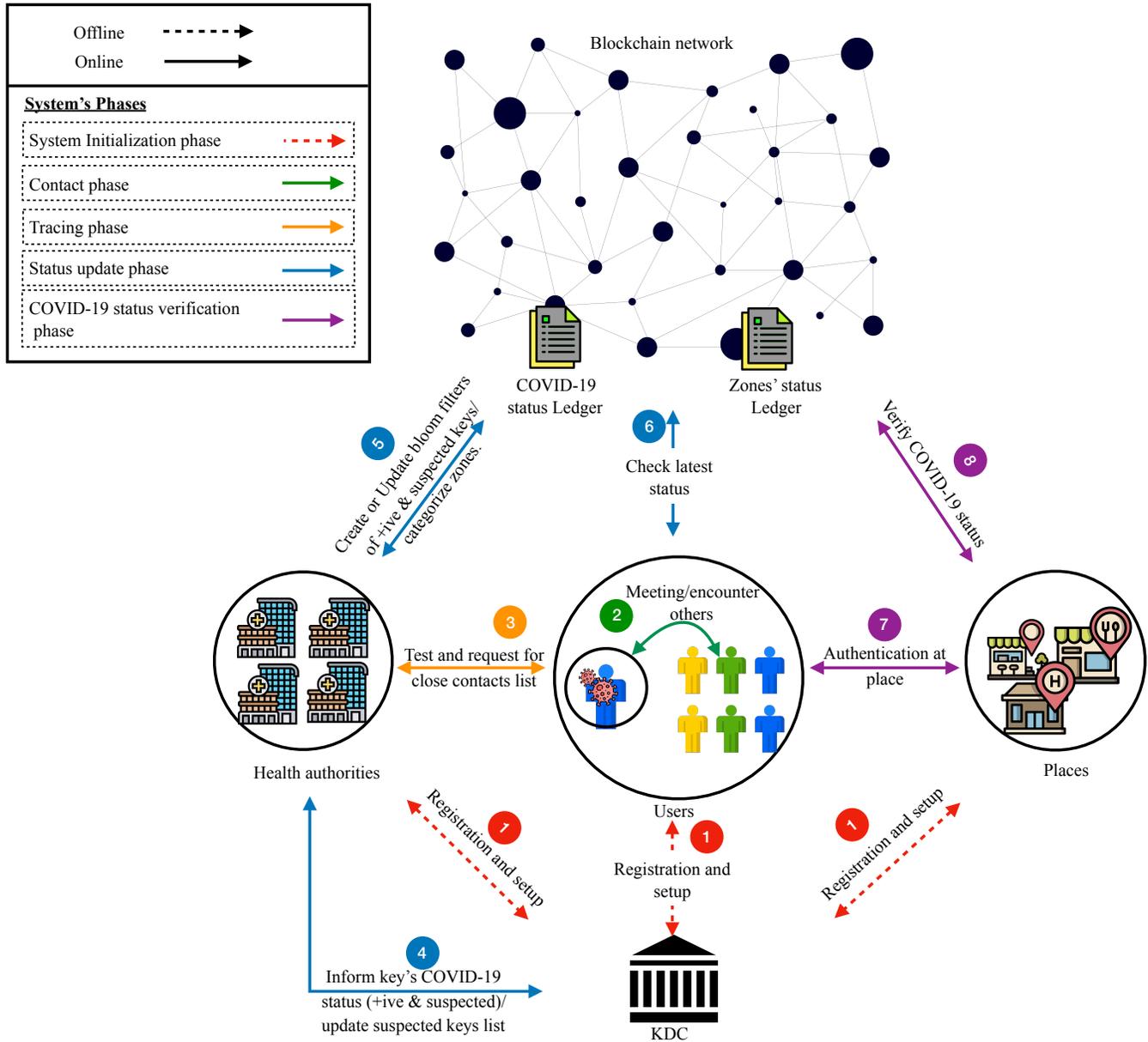


Fig. 2: An illustration for the network model.

B. Threat Model

The KDC executes the system initialization and key renewal processes correctly because it can be administrated by the ministry of health which is naturally interested in controlling the virus spread. However, the KDC is curious to learn sensitive information about the users. The health authorities are honest-but-curious, i.e., they run the system correctly, but they are curious to learn sensitive information about the users. The health authorities do not trust each other and they act as validators in the Blockchain network. Users are curious to learn sensitive information on other users, and they may also launch panic attacks by reporting false close contacts. In addition to the previous internal entities, adversaries can also be external attackers who try to learn sensitive information by eavesdropping on all the communications in the system.

Adversaries may try to launch the following attacks.

- **Identification.** An adversary may try to identify the real identities of the users. He may also try to learn whether a person of interest is infected with COVID-19 or was in close contact of an infected user.
- **Social graph disclosure.** An adversary may try to identify the social graph of an infected user, i.e., identify the close contacts of this user.
- **Tracking.** An adversary may try to track the locations of a user using the information acquired from the messages exchanges in the system.
- **False reporting of close contacts.** An adversary may try to deceive the health authority to falsely identify users as close contacts of an infected user.
- **Message modification and manipulation.** An adversary may try to modify, manipulate, or replay messages that are exchanged in the system.

C. Design Goals

Our system is designed to achieve the following goals.

- **Decentralization.** Given the vulnerabilities of the centralized architectures in terms of single point of failure and DoS attacks, our system should be decentralized to enhance the availability and the reliability of the provided services. In other words, our system should not depend on a single central authority to conduct the contact tracing process, update the infection status of users, and categorize zones.
- **Privacy Preservation.** The privacy of all users, including both infected users and their close contacts, should be preserved. Specifically, no one including the health authority should identify the close contacts of any infected user. Moreover, no one should be able to track the visited locations of any user in the system. Therefore, our system should be secure against privacy attacks including identification, social graph disclosure, and tracking.
- **Infection Control.** Our system should control the infection spread between people as follows.
 - *Tracing and notification.* Our system should notify the users who closely contacted an infected user during the incubation period of the virus to quarantine.
 - *Countering non-compliance.* Infected users and their close contacts should quarantine until they are tested negative to avoid spreading the virus. Our system should prevent non-compliant users (i.e., infected users and their close contacts who do not quarantine) from accessing public places and engaging with healthy people.
 - *Recommending safe places.* Our system should classify zones based on their infection level so that users avoid contaminated zones, i.e., zones with high number of infections, to avoid spreading the virus.
- **Prevention of panic attacks.** The system should be secure against panic attacks launched by reporting false close contacts. To do that, the system should ensure that there were real contacts between the users and their close contacts.
- **Transparency.** The system should be transparent and verifiable in the processes of updating users' status and zones' infection levels.
- **Efficiency and scalability.** In pandemics, many people usually get infected, so our system should be scalable, i.e., efficient in terms of communication, computation, and storage overheads.

IV. PROPOSED INFECTION CONTROL SYSTEM

In this section, we present our secure and privacy-preserving Blockchain-based infection control system.

A. Overview

As demonstrated in Fig. 2, there are five phases in our system, including *system initialization*, *contact*, *tracing*, *status update/check*, and *public places access control*.

In the *system initialization* phase, the KDC distributes cryptographic credentials to the system entities. Users should

contact the KDC frequently to renew their credentials. In the *contact* phase, when two users encounter each other, they authenticate and check the COVID-19 status of each other, and then exchange proof-of-contact messages containing the location and time of the contact. In the *tracing* phase, if a user is tested positive for COVID-19 by a health authority, he/she should send all the contact messages collected in the past 14 days to the health authority. In the *status/check update* phase, the health authorities use the proof-of-contact messages provided by the infected users to update the status of the infected users and their close contacts and categorize the zones based on their infection level, and post the updates on the Blockchain. The Blockchain is queried to check the status of users or infection level of zones. In the *public places access control* phase, to control the spread of the virus, before allowing a user to enter a public place and engage with other people, the infection status of the user is checked first.

B. System Initialization Phase

The KDC generates the bilinear pairing parameters $\{q, \mathbb{G}, \mathbb{G}_T, P, e\}$ and chooses a secure hash function \mathcal{H} , where $\mathcal{H}: \{0, 1\}^* \rightarrow \mathbb{G}$, \mathbb{G} is a cyclic additive group of prime order q and has a generator P , \mathbb{G}_T is a cyclic multiplicative group of the same prime order q , and $e: \mathbb{G} \times \mathbb{G} \rightarrow \mathbb{G}_T$. Then, it publishes the system parameters as $\{q, \mathbb{G}, \mathbb{G}_T, P, e, \mathcal{H}\}$. Each health authority (H) and public place (P) register with the KDC to obtain long-term certified public and private key pairs $\mathcal{PK}_H/\mathcal{SK}_H$ and $\mathcal{PK}_P/\mathcal{SK}_P$, respectively, where $\mathcal{SK}_H = x_H$, $\mathcal{SK}_P = x_P$, $\mathcal{PK}_H = x_H P$, and $\mathcal{PK}_P = x_P P$, and $x_H, x_P \in \mathbb{Z}_q^*$. Each user (U) should obtain a pseudo identity and short-term public and private key pair $(T_{\mathcal{PK}_U}, T_{\mathcal{SK}_U})$ and certificate $(Cert_U)$, where $T_{\mathcal{SK}_U} = x_U$, $T_{\mathcal{PK}_U} = x_U P$, and $x_U \in \mathbb{Z}_q^*$. Before a user's certificate expires, he/she should contact the KDC to obtain a new short-term pseudo identity, public and private key pair, and certificate. Each user's credential should be used for a short time and no one (except the KDC) should be able to link a user's credentials to preserve the privacy of the users. The KDC should not renew the credentials of the infected or suspected users until they are tested negative for COVID-19.

C. Contact Phase

In our system, we consider both direct and indirect infections. Direct infection happens when an individual contracts the virus due to getting close and engaging with infected individuals, while indirect infection happens when an individual contracts the virus due to visiting public places that have been recently visited by infected individuals. In the latter case, individuals may get infected by touching surfaces contaminated with COVID-19 and then touching their mouths, noses, or eyes.

Direct infections. Before two users get closer to each other or engage in any activity, each user needs to make sure that the other user is healthy (non-infected). To do so, each user first checks that he/she is meeting a legitimate user with a valid public key certificate. Then, each user needs to check the COVID-19 status of the other user by sending a request

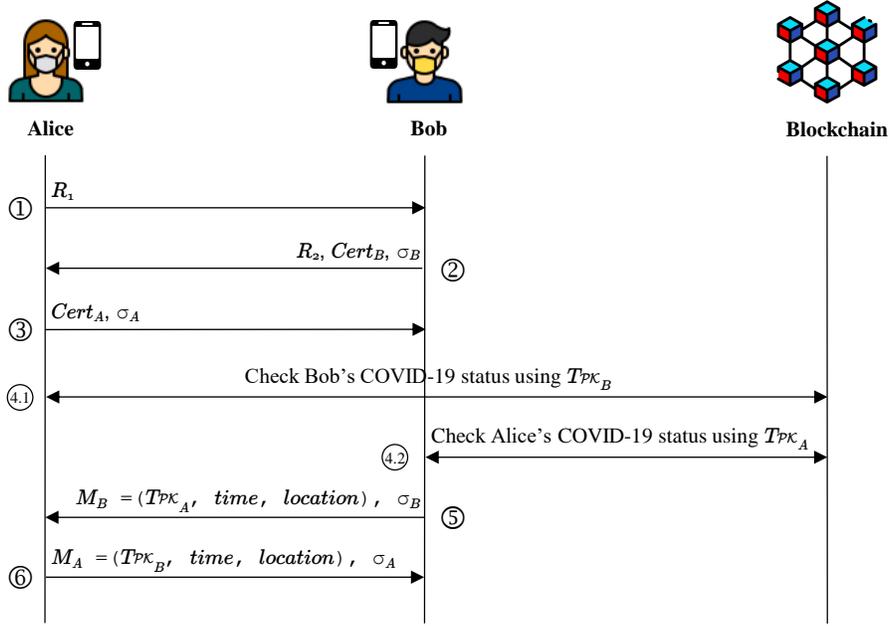


Fig. 3: An illustration for the exchanged messages in the *contact* phase.

to the Blockchain with the public key of the other user. If the Blockchain returns that the COVID-19 status of the two users are negative, they use Bluetooth to exchange proof-of-contact messages to be stored in their smartphones. These messages will be used later to notify the users that were in close contact within the last 14 days to someone who is tested positive for COVID-19.

In the following, we explain the steps of the *contact* phase executed by two users (Alice and Bob). The messages exchanged between the system entities involved in this phase are shown in Fig. 3:

Step ①: Alice sends a random number R_1 to Bob.

Step ②:

- Bob uses his temporary private key, $T_{SK_B} = x_B$, to sign R_1 as follows.

$$\sigma_B = x_B \mathcal{H}(R_1). \quad (2)$$

- Bob sends the certificate of his temporary public key ($Cert_B$) and signature (σ_B) to authenticate himself to Alice. Moreover, Bob sends a random number R_2 to Alice to sign so that he can authenticate Alice.
- Alice validates the certificate of Bob ($Cert_B$) by verifying the KDC's signature on the certificate using the KDC's public key, and checking whether the certificate is expired.
- If the certificate is valid, then Alice proceeds by verifying Bob's signature; otherwise, Alice should not continue the protocol or engage with Bob in any activity. Alice uses the public key included in Bob's digital certificate, $T_{PK_B} = Y_B$, to verify the received signature (σ_B) by checking the following.

$$e(\sigma_B, P) \stackrel{?}{=} e(\mathcal{H}(R_1), Y_B) \quad (3)$$

Proof.

$$\begin{aligned} e(\sigma_B, P) &= e(x_B \mathcal{H}(R_1), P) \\ &= e(\mathcal{H}(R_1), x_B P) \\ &= e((\mathcal{H}(R_1), Y_B)). \end{aligned}$$

Step ③: Alice responds to Bob with the certificate of her temporary public key ($Cert_A$) and signature (σ_A) on both R_1 and R_2 . Similarly, Bob verifies $Cert_A$ and σ_A .

Step ④: Alice checks the COVID-19 status of Bob by sending a request to the Blockchain containing Bob's temporary public key T_{PK_B} . The Blockchain returns “infected”, “close contact”, or “not found” based on the status of the user. If the status of Bob is “infected” or “close contact”, then Alice terminates the protocol and should not get closer to Bob or engage in an activity with him. However, if the status is “not found”, this indicates that it is safe for Alice to meet Bob. Similarly, Bob repeats these steps to check the COVID-19 status of Alice.

Step ⑤:

- Bob composes a proof-of-contact message ($M_B = T_{PK_A}, time, location$), containing the public key of Alice and the time and location of the contact. Then, Bob sends M_B and a signature on it ($\sigma_B = x_B \mathcal{H}(M_B)$) to Alice. The signature σ_B is needed as a proof for the contact of Alice and Bob to prevent the false reporting (or panic) attack and also to guarantee the authenticity and integrity of the message.
- Alice accepts M_B if the signature σ_B is valid. Then, the message M_B associated with the signature σ_B and Bob's temporary public key certificate ($M_B, \sigma_B, Cert_B$) is stored in Alice's smartphone.

Step ⑥: Alice, similarly, sends a contact message M_A and a signature σ_A to Bob. If the signature σ_A is valid, the tuple ($M_A, \sigma_A, Cert_A$) is stored in Bob's smartphone.

Indirect infections. When a user visits a public place, regardless of encountering other users, he/she should exchange a proof-of-visiting message with the place itself, which indicates that he/she has visited the place in a specific time period. When Alice visits a restaurant R , she receives a proof-of-visiting message ($M_R = T_{\mathcal{PK}_A}, time, location$) and a signature on it ($\sigma_R = x_R \mathcal{H}(M_R)$). The tuple $(M_R, \sigma_R, Cert_R)$ is stored in Alice's smartphone if the received signature σ_R is valid, where $Cert_R$ is the public key certificate of the restaurant. Similarly, a proof-of-visiting tuple $(M_A, \sigma_A, Cert_A)$ is stored in the restaurant's local storage.

In order to reduce the storage overhead on the users' smartphones, we use an aggregate signature technique. Every time a user receives a signed message either from other users or visited places, he aggregates the signature of this message with the signatures stored in his smartphone. Assume that the user U has collected \mathcal{M} messages. Instead of storing \mathcal{M} individual signatures, the user stores only one aggregate signature (σ_{agg}), where the size of σ_{agg} is similar to the size of each individual signature. σ_{agg} is calculated as follows.

$$\sigma_{agg} = \sum_{i=1}^{\mathcal{M}} x_i \mathcal{H}(T_{\mathcal{PK}_{U_i}}, time_i, location_i) \quad (4)$$

D. Tracing Phase

In this phase, the health authority collects all the proof-of-contact and proof-of-contact messages from the infected users.

Direct infections. If a user is tested positive for COVID-19, he/she should send the proof-of-contact and proof-of-visiting messages collected in the last 14 days to the health authority to notify the close-contact users. Assume that the number of collected messages by the user in the last 14 days is \mathcal{N} . These messages are stored in the user's smartphones as groups of \mathcal{M} messages, where each group is associated with an aggregate signature σ_{agg} . When a user sends his messages to the health authority, he sends them at different times (only one group at a time) so that the health authority cannot know if the messages are sent from same user or different users because it cannot link the short-term public keys used by the same user.

The user U uploads the following data to the health authority: $\{M_1, M_2, \dots, M_{\mathcal{M}}\}$ and σ_{agg} , where $M_i = (T_{\mathcal{PK}_{U_i}}, time_i, location_i, Cert_i)$. Using the aggregate signature reduces the communication overhead because the user uploads only one signature instead of uploading \mathcal{M} individual signatures. Once the user uploads proof-of-contact messages, the health authority needs to check the authenticity and integrity of all messages to make sure that the user is not launching a false reporting attack.

Moreover, using the aggregate signature reduces the computation overhead because the health authority verifies only one signature σ_{agg} instead of verifying \mathcal{M} signatures. If σ_{agg} is valid, this indicates that all the underlying individual signatures are valid. To verify the aggregate signature σ_{agg} , the health authority checks the following.

$$e(\sigma_{agg}, P) \stackrel{?}{=} \prod_{i=1}^{\mathcal{M}} e(\mathcal{H}(T_{\mathcal{PK}_{U_i}} || time_i || location_i), Y_i) \quad (5)$$

Proof.

$$\begin{aligned} e(\sigma_{agg}, P) &= e\left(\sum_{i=1}^{\mathcal{M}} x_i \mathcal{H}(T_{\mathcal{PK}_{U_i}}, time_i, location_i), P\right) \\ &= \prod_{i=1}^{\mathcal{M}} e(x_i \mathcal{H}(T_{\mathcal{PK}_{U_i}}, time_i, location_i), P) \\ &= \prod_{i=1}^{\mathcal{M}} e(\mathcal{H}(T_{\mathcal{PK}_{U_i}}, time_i, location_i), x_i P) \\ &= \prod_{i=1}^{\mathcal{M}} e(\mathcal{H}(T_{\mathcal{PK}_{U_i}}, time_i, location_i), Y_i). \end{aligned}$$

Indirect infections. After verifying the proof-of-visiting messages containing the places visited by the infected users in the last 14 days, the health authority traces the probable indirect infections. To do that, it requests these places to send the proof-of-visiting messages collected from the users that visited the places at the same time frame as the infected user. Also, because COVID-19 virus can survive on surfaces for several hours, the place can also send the proof-of-visiting messages for several hours after the visit of the infected user.

The collected information in this phase is used in the *status update/check phase* to update the COVID-19 status of the infected users and their close contacts, and also categorize the infection level of the different zones.

E. Status Update/Check Phase

1) *Status Update:* After a health authority verifies the received messages from infected users and their visited places, it forwards these messages to the other health authorities which act as validators in the Blockchain network to verify them. One of these health authorities is elected to act as a leader based on the Raft consensus algorithm. The leader adds the public keys of the infected and close-contact users in two Bloom filter lists; one contains the keys of the infected users and the other contains the keys of the close contacts users. Because a contact may have happened in the past 14 days and due to using short-term certificates, some public keys may have expired and the users have renewed them. In this case, to obtain the latest public key of a user, the leader retrieves it from the KDC without revealing the location and time of the contact and also the public key of the other user in the contact. This is important to preserve privacy because the KDC can link the short-term keys to the real identity of the users and by receiving these information it can know who met whom, where, and when and build a social graph.

Fig. 4 illustrates the steps of updating the users' COVID-19 status and the infection level of the zones. These steps are explained as follow.

Step ①: The leader sends the public keys of the users with expired certificates to the KDC.

Step ②: The KDC stops renewing the keys of those users until they are tested negative for COVID-19, and responds to the leader with the latest public keys of the users.

Step ③: The leader updates two Bloom filters using the latest keys; one for the infected users and the other for the

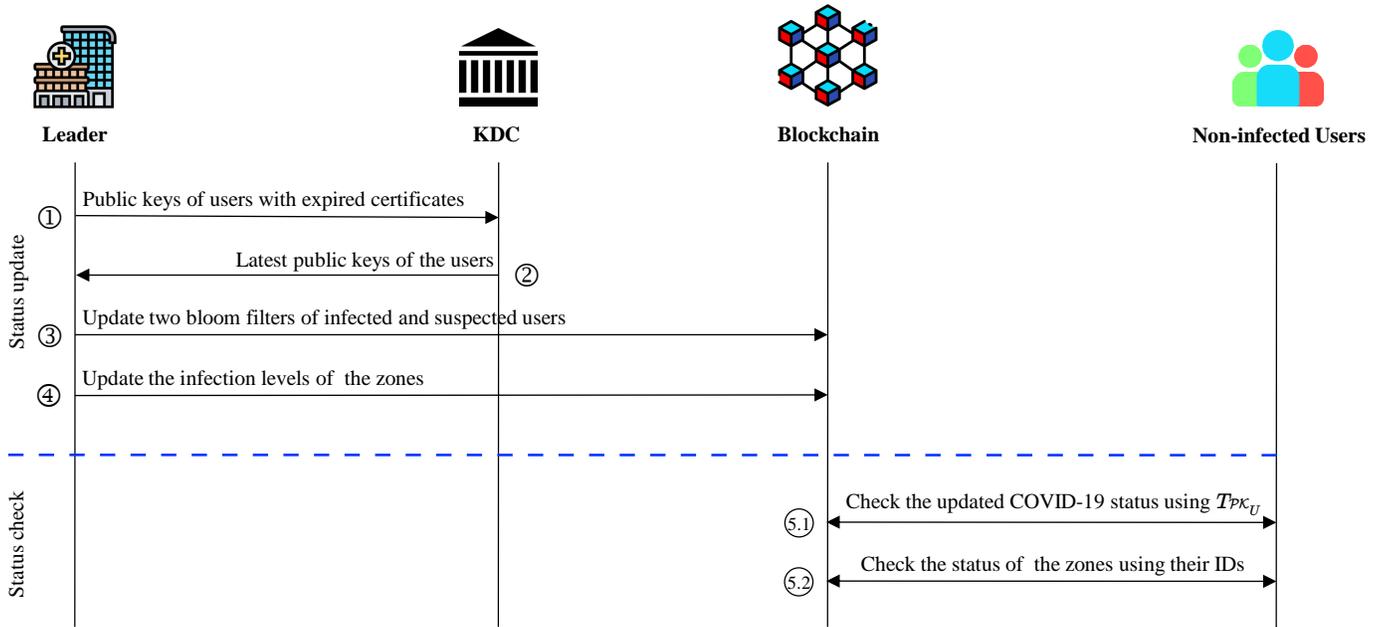


Fig. 4: An illustration for the *status update/check* phase.

suspected users. These Bloom filters are broadcasted to the follower validators in the form of a proposed block to be appended to the COVID-19 status ledger. Each follower votes for the new block and the leader waits for the majority of the votes to add the new block to the ledger. Finally, the new block is signed by the leader and broadcasted to the followers to be added to their copies of the ledger.

Step ④: In our system, each city is divided into small geographic areas called zones, where each zone has a unique identifier. To determine the category of a zone, the weighted average of the number of infected and suspected users in the last 14 days is calculated and compared to two thresholds (Th_1 and Th_2), where $Th_2 > Th_1$. If the weighted average of a zone is greater than Th_2 , then the zone's status is *red*. If the weighted average of a zone is greater than Th_1 and less than Th_2 , then the zone's status is *orange*. Otherwise, the zone's status is *green*. After that, the leader creates a new block containing the zones' identifiers (IDs), their updated average infection numbers, and their updated status. This new block is broadcasted to the Blockchain followers to be approved and appended to the zones status ledger.

2) *Status check:* Fig. 4 shows the exchanged messages between the users and the Blockchain to check the COVID-19 status of the users and zones status.

Step ⑤: A non-infected user U can check his/her updated COVID-19 status by sending a request to the Blockchain containing his/her latest temporary public key T_{PK_U} . If T_{PK_U} is found in the Bloom filter of suspected users, this indicates that the user has closely contacted (in the last 14 days) someone who is tested positive for COVID-19, and thus he/she needs to quarantine immediately and visit a health authority to take COVID-19 test. If a suspected user is tested negative, the health authority should make a transaction to remove the temporary public key of this user from the list of suspected users (close contacts). Once a user is removed from the lists

of infected or suspected users, the KDC resumes renewing his/her keys so that he/she can access public places. On the other hand, if the suspected user is tested positive, the user is required to send his/her messages collected in the last 14 days, and his/her temporary public key should be moved to the Bloom filter of infected users. Furthermore, non-infected users can check the status of a zone they want to visit by sending a request to the Blockchain containing the zone's ID.

F. Public Places Access Control Phase

In this phase, a public place checks COVID-19 status of the users before allowing them to access the place. If the status is negative, the user can enter the place; otherwise, the user is not allowed to enter the place to prevent spreading the virus. Therefore, the COVID-19 status is used as a *digital pass* to prevent infected and suspected users from accessing public places. Fig. 5 shows the messages exchanged between users and public places. Specifically, when a user visits a public place, the following steps are executed.

Step ①: The user sends a random number (R_1) to the public place.

Step ②: The place signs R_1 and sends its certificate $Cert_P$, the signature σ_P , and a random number (R_2) to the user. Then, the user verifies the certificate $Cert_P$ and the σ_P .

Step ③: The user signs R_2 and sends his/her temporary public key certificate $Cert_U$ and the signature σ_U to be authenticated by the place.

Step ④: After the mutual authentication, the place checks the COVID-19 status of the user by sending a request to the Blockchain containing the user's temporary public key T_{PK_U} .

Step ⑤: If T_{PK_U} is not found in any of the two filters, this indicates that the COVID-19 status of the user is negative, and thus the user can access the public place. Otherwise, the user is banned from accessing the place to avoid spreading the virus to other users.

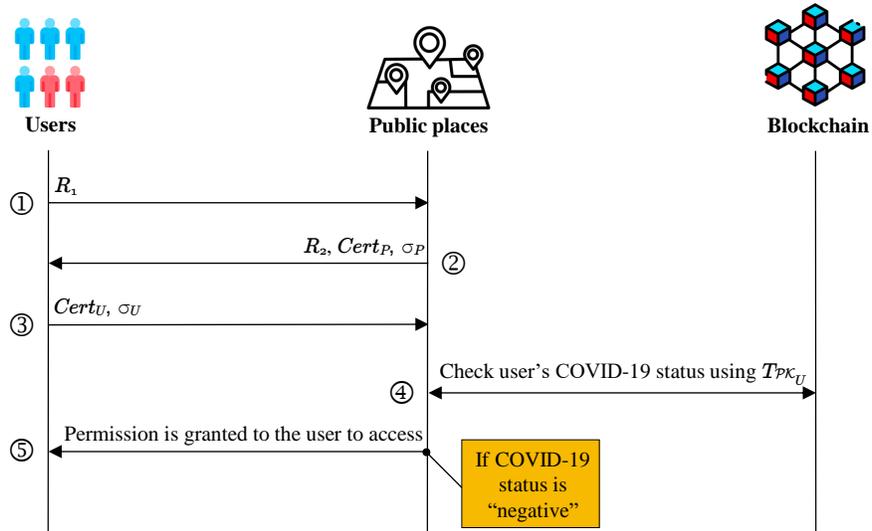


Fig. 5: An illustration for the *public places access control* phase.

V. SECURITY AND PRIVACY ANALYSIS

In this section, we analyze the security and privacy features provided by our system.

Proposition 1. *Our system ensures the availability and reliability of the provided services.*

Proof. Instead of depending on a single central authority to update the COVID-19 status of the users and categorize zones based on infection levels, our system is decentralized and run by a group of health authorities that form a consortium Blockchain. Utilizing the Blockchain technology makes our system resilient against the single point of failure problem and the DoS attacks threatening the availability of the provided services. This is because for an adversary to make the services unavailable, it is not sufficient to attack a single node as it is the case in the centralized system. Moreover, utilizing the Blockchain enhances the reliability of the provided services. This is because it is impossible for an adversary to change the content of the Blockchain ledger without compromising the majority of the Blockchain nodes.

Proposition 2. *Our system thwarts the identification attack that aims to disclose a user's COVID-19 status.*

Proof. In our system, the real identities of the users are hidden. Instead, unlikable pseudo-identities and short-term public keys are used to provide anonymity to the users. In the COVID-19 *status update/check* phase of our system, only the latest keys of the infected and suspected users are stored in the Bloom filters. Therefore, if an attacker wants to track the COVID-19 status of a particular user, he cannot do that because he does not know the short-term public keys used by the user. However, for traceability of COVID-19 infections, when two users encounter each other, they need to exchange their short-term public keys. Moreover, if a user's status is updated to "suspected", he cannot learn the user who infected him because users frequently change their keys and only the last key (which is not linkable to the old keys) is stored in the Bloom filter on the Blockchain.

Proposition 3. *Our system thwarts the social graph disclosure and tracking attacks.*

Proof. The social graph disclosure attacks aim to identify the close contacts of an infected user, and the tracking attacks aim to track users' movements and activities using the location data of the proof-of-contact and proof-of-location messages. In the *tracing* phase of our system, if a user is tested positive for COVID-19, he sends the proof-of-contact and proof-of-visiting messages collected from his/her close contacts and visited places to the health authority. Using these messages, the healthy authority cannot create a social graph for the close contacts of the user. This is because pseudo-identities and short-term public keys are used, so if the user meets another user multiple times, the health authority cannot figure out this information because it cannot link the short-term public keys used by the same user. Moreover, when a user sends his proof-of-contact and proof-of-visiting messages to the health authority, he sends them at different times so that the health authority cannot know if the messages are sent from same user or different users to prevent it from even learning the pseudo-identities of a user's close contacts. Moreover, since the KDC can link the short-term public keys of each user, when the health authority resolves the latest public keys of the users in the *status update/check* phase, it only forwards the public keys to the KDC and it does not forward the location information to prevent the KDC from learning the locations visited by each user. The health authority should also shuffle the public keys of different users before sending them to the KDC so that it cannot learn the users who contacted each other.

Proposition 4. *Our system allows only authorized and healthy (non-infected) users to interact with other users and access public places.*

Proof. The KDC issues a certified public and private key pair $(T_{PK_{U_i}}, T_{SK_{U_i}})$ for each user to be able to participate in the system, i.e., be able to interact with other users and access public places. Each user needs to authenticate to other users to interact with them and authenticate to the public places to access them. Therefore, if a user does not have valid

credentials, he cannot participate in the system. Moreover, if a user is tested positive for COVID-19 or closely contacted an infected user, he cannot contact other users or access public places because the COVID-19 status of the users are checked before encountering other users and entering public places. The KDC also does not issue new certificates for these users until they are removed from the lists of infected and suspected (close-contact) users.

Proposition 5. *Our system is resilient against false reporting (or panic) attack that aims to falsely classify victim users as close contacts.*

Proof. In our system, each proof-of-contact (or proof-of-visiting) message includes a signature from the close-contact user (or public place), so to report false contacts to the health authority, the attacker should forge the signature of the victim user. This is impossible in our system without knowing the private key of the victim user. It is also impossible to compute the private key from the public key of the victim user under the known difficulty of computing the elliptic curve discrete logarithm [29]. In addition, since the signatures of the proof-of-contact messages have a time stamp and the public key of the other user, attackers cannot use them for different users or different times, i.e., if a contact happened more than 14 days ago, attackers cannot alter the time and claim that the contact is recent. Thus, adversaries cannot falsely claim that they have encountered users.

Proposition 6. *The process of updating COVID-19 status and zone's status is transparent and verifiable.*

Proof. Blockchain brings transparency to our system by not trusting a single entity (health authority) to update COVID-19 status and zone's status. In fact, all transactions (proof-of-contact and proof-of-visiting messages), the updated lists of infected and close-contact users, and the updated zone categorization are verified by all the Blockchain nodes, and the majority of the validators should approve them. As explained earlier, the leader health authority is responsible for creating blocks containing two Bloom filters for the COVID-19 status of the users and another blocks containing the updated status of zones. These blocks are broadcasted to the Blockchain network and the leader needs to get the votes of the majority of the validators before appending the blocks to the corresponding ledgers. Therefore, a malicious health authority cannot manipulate the lists and the zone categorization.

VI. PERFORMANCE EVALUATION

In this section, the performance of our system is evaluated and compared to other systems.

A. Experimental setup and performance metrics

The signature scheme used in our system is based on the elliptic curve cryptography [30]. In our evaluations, we use 224-bit elliptic curve and SHA-224 hash function. Thus, the sizes of public key, private key, hash value, and signature are given in Table I. Moreover, the sizes of other data items used in our system, including random number, location, and time are also given in in Table I. In our experiments, we

TABLE I: Sizes of the data used in our system.

Data	Size (bytes)
Random number	5
Private key	28
Public key	29
Public key certificate	93
Hash	28
Signature	56
Location	6
Time	8

TABLE II: Computation times of the cryptographic operations.

Cryptographic operation	Time (ms)
<i>Pairing</i>	3.139
<i>Hash</i>	0.058
<i>Add</i>	0.000227
<i>Mul</i>	0.000269
<i>Exp</i>	0.334

TABLE III: Sizes of the messages exchanged in the *contact* phase.

Message	①	②	③	④	⑤	⑥
Size (bytes)	5	154	149	29	29	99

have used the Charm Python library [31] to calculate the time required to implement the different cryptographic operations including bilinear pairing (*Pairing*), hashing (*Hash*), addition (*Add*), multiplication (*Mul*), and exponentiation (*Exp*). The experiments have been conducted on Raspberry Pi 3 device with 1.2 GHz processor and 1 GB RAM. The time required to run the different cryptographic operations are given in Table II.

For the performance metrics, we evaluate our system in terms of communication, computation, and storage overheads.

- **Communication overhead.** The sizes of the messages exchanged between the system entities.
- **Computation overhead.** The time required to perform the steps of the system phases.
- **Storage overhead.** The memory space required to store the data of our system.

B. Communication Overhead

1) **Contact Phase:** Fig. 3 shows the exchanged messages between the system entities involved in the *tracing* phase. From Table I, we can calculate the sizes of these messages as given in Table III. The table demonstrates that our system requires exchanging small messages in the *contact* phase.

2) **Tracing Phase:** In this phase, the infected user uploads proof-of-contact and proof-of-visiting messages collected in the last 14 days (\mathcal{N}) as groups of \mathcal{M} messages, where these groups are uploaded at different times. The size of each group is $(\mathcal{M} \times 136 + 56)$ bytes. Thus, the communication overhead is $(\frac{\mathcal{N}}{\mathcal{M}} \times (\mathcal{M} \times 136 + 56)) = (136\mathcal{N} + 56\mathcal{M})$ bytes. Without using the signature aggregation technique, the overhead would be $192\mathcal{N}$. The health authority broadcasts these messages to the other health authorities in the Blockchain network nodes (validators) to verify. Thus, the communication overhead on the Blockchain validators is also $(136\mathcal{N} + 56\mathcal{M})$ bytes.

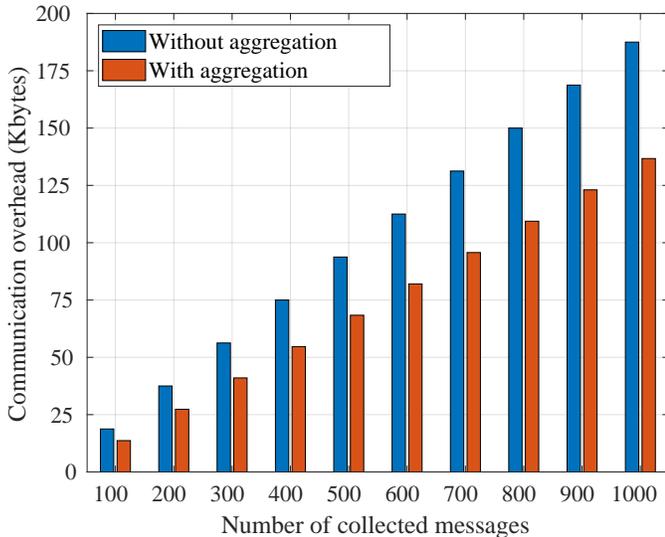


Fig. 6: The communication overhead on the Blockchain validators with and without using aggregation.

TABLE IV: Sizes of the messages exchanged in the *status update/check* phase.

Message	①	②	③	④	⑤.1	⑤.2
Size (bytes)	$(29\mathcal{V})$	$(29\mathcal{V})$	$(10N_1 + 10N_2)/8$	$(6\mathcal{Z})$	29	2

Note: - means that the message size is negligible.

To illustrate the importance of using signature aggregation technique, Fig. 6 compares between the communication overhead on the Blockchain validators with and without using aggregation at different numbers of messages in case $\mathcal{M} = \mathcal{N}/14$. The figure shows that the signature aggregation technique considerably reduces the communication overhead. For example, when the number of messages is 300, the communication overhead with aggregation is only 41Kbytes, while it is 56Kbytes without aggregation. In other words, *using the signature aggregation technique reduces the communication overhead by 27%*.

3) **Status Update/Check Phase:** Fig. 4 shows the exchanged messages between the system entities in the *status update/check* phase. From Table I, we can calculate the sizes of these messages as given in Table IV. The communication overhead of step ① or ② is $(29\mathcal{V})$ bytes, where \mathcal{V} is the number of keys with expired certificates. In step ③, the leader broadcasts two updated Bloom filters to the Blockchain followers. Thus, the communication overhead of step ③ depends on the sizes of the Bloom filters. As explained in Section II-C, there is a probability of false positive when we check if an element is stored in the filter. According to Eq. 1, this probability depends on the number of hash functions (k), the size of the filter in bits (m), and the number of elements stored in the filter (n). In our system, we use five hash functions ($k = 5$) and adaptive filter size that depends on the number of elements stored in the filter to keep the false positive probability low. Fig. 7 illustrates the relation between the false positive probability and the size of the filter

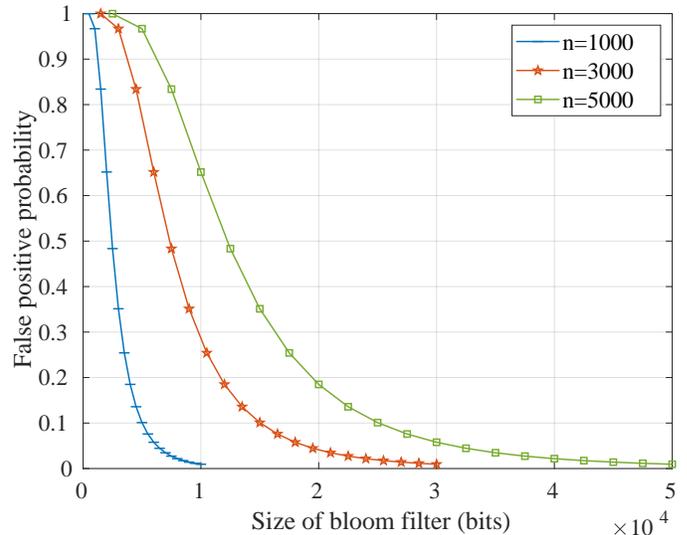


Fig. 7: The relation between the false positive probability and the Bloom filter size at different numbers of public keys.

TABLE V: Sizes of the messages exchanged in the *public places access control* phase.

Message	①	②	③	④	⑤
Size (bytes)	5	154	149	29	-

Note: - means that the message size is negligible.

at different numbers of stored elements. We can observe from Fig. 7 that the larger the size of the filter, the lower the false positive probability. We can also observe that the false positive probability is close to zero when the filter size is ten times the number of elements. Thus, the communication overhead of step ③ is approximately equal to $((10N_1 + 10N_2)/8)$ bytes, where N_1 and N_2 are the number of infected and suspected users, respectively.

In step ④, the leader broadcasts the zones's IDs and their updated status to the Blockchain followers. Thus, the communication overhead of step ④ is approximately equal to $(6\mathcal{Z})$ bytes, where \mathcal{Z} is the number of the zones and each of zone's ID, number of infected users, and number of suspected users and the status is represented by 2 bytes. In step ⑤, a non-infected user can check his updated COVID-19 status by sending his temporary public key to the Blockchain or check a zone status by sending the zone ID to the Blockchain. In case that the non-infected user checks the COVID-19 status, the communication overhead of step ⑤.1 is approximately equal to 29 bytes. In case that the non-infected user checks the zone status, the communication overhead of step ⑤.2 is approximately equal to 2 bytes because the user sends a 2-byte zone ID to the Blockchain.

4) **Public Places Access Control Phase:** Fig. 5 shows the exchanged messages between the system entities involved in the *Public Places Access Control* phase. From Table I, we can calculate the sizes of these messages and the results are given in Table V. Overall, we can conclude that our system requires exchanging small-size messages in this phase.

TABLE VI: Computation times of the steps of the *contact* phase.

Step	①	②	③	④.1	④.2	⑤	⑥
Time (msec)	-	12.6	12.6	0.29	0.29	6.3	6.3

Note: - means that the computation time is negligible.

C. Computation Overhead

1) **Contact Phase:** Using the computational times in Table II, we can compute the computation times of the steps of the *contact* phase and the results are given in Table VI. In step ② or ③, one user computes a signature and the other user verifies the certificate (by verifying the KDC's signature) and the signature of the user. According to Eq. 2, the computation of a signature requires one *Hash* and one *Mul* operations; thus, the computation time is $0.058 + 0.000269 \approx 0.0583$ msec. According to Eq. 3, the verification of a signature requires two *Pairing* operations; thus, the verification time is $2 \times 3.139 = 6.278$ msec. The computation overhead of step ② or ③ is $0.0583 + 2 \times 6.278 \approx 12.6$ msec. In step ④, for the Blockchain to return the COVID-19 status of the user, it is required to compute k hash functions to search for the user's key in the Bloom filters. In our system, we use $k = 5$; thus, the computation overhead of step ④ is $5 \times 0.058 = 0.29$ msec. In step ⑤ or ⑥, one user sends a proof-of-contact message signed with his/her temporary private key and the other user verifies the signature; thus, the computation overhead of ⑤ or ⑥ is $0.0583 + 6.278 \approx 6.3$ msec.

2) **Tracing Phase:** In this phase, after receiving \mathcal{M} messages from the infected user, the health authority verifies only one aggregate signature (σ_{agg}) instead of verifying \mathcal{M} individual signatures. According to Eq. 4, the verification of σ_{agg} requires $\mathcal{M} + 1$ *Pairing* operations; thus, the verification time is $3.139(\mathcal{M} + 1)$ msec. The total computation overhead is $(\frac{\mathcal{N}}{\mathcal{M}} \times 3.139(\mathcal{M} + 1))$ msec. On the other hand, the computation overhead would be $\mathcal{N} \times 2 \times 3.139$ msec without using the signature aggregation technique, where the verification of each signature requires two *Pairing* operations according to Eq. 3.

After verifying the messages uploaded from an infected user, the health authority broadcasts these messages to the other Blockchain validators to verify. Thus, the computation overhead on each Blockchain validator is also $(\frac{\mathcal{N}}{\mathcal{M}} \times 3.139(\mathcal{M} + 1))$ msec. To evaluate the reduction in the computation overhead due to using the signature aggregation technique, in Fig. 8, we compare between the computation overhead on the Blockchain validators with and without using aggregation at different numbers of messages (in case $\mathcal{M} = \mathcal{N}/14$). The figure shows that the signature aggregation technique considerably reduces the computation overhead. For example, when the number of messages is 300, the computation overhead with aggregation is approximately 1 sec, which is nearly half the computation overhead without aggregation. In other words, *using the signature aggregation technique results in about 48% reduction in the computation overhead.*

3) **Status Update/Check Phase:** In step ③ of the *status update/check* phase, for the leader to create a Bloom filter, he needs to calculate five *Hash* operations for each public key to

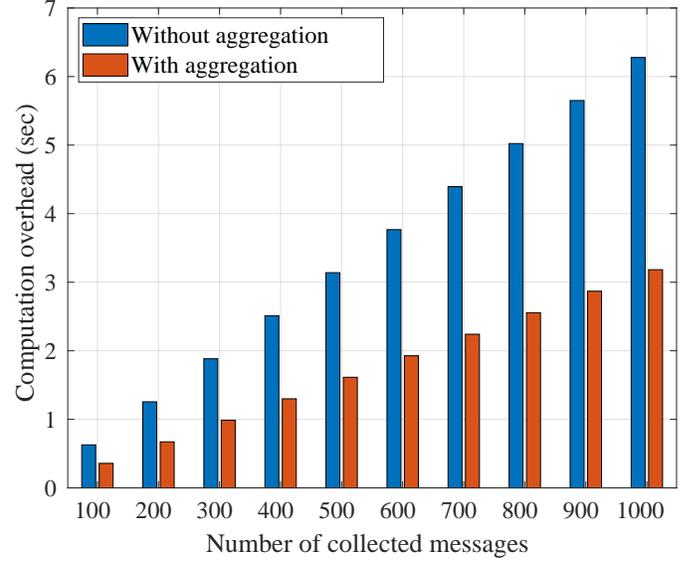


Fig. 8: The computation overhead on the Blockchain validators with and without using aggregation.

TABLE VII: Computation times of the steps of the *status update/check* phase.

Step	①	②	③	④	⑤.1	⑤.2
Time (msec)	-	-	$0.29(N_1 + N_2)$	-	0.29	-

Note: - means that the computation time is negligible.

TABLE VIII: Computation times of the steps of the *public places access control* phase.

Step	①	②	③	④	⑤
Time (msec)	-	12.6	12.6	0.29	-

Note: - means that the computation time is negligible.

be stored in the filter; thus, the computation overhead of step ③ is $(5 \times 0.058 \times (N_1 + N_2)) = 0.29(N_1 + N_2)$ msec.

4) **Public Places Access Control Phase:** Using Table II, we can compute the computation times of the steps of the *public places access control* phase, and the results are given in Table VIII. The table shows that the computation times of this phase are acceptable.

D. Storage Overhead

1) **Off-Chain Storage:** Upon the completion of the *contact* phase, the user stores the tuple $(M_i, \sigma_i, Cert_i)$ in his/her smart phone as a proof-of-contact. The size of this tuple is $43 + 56 + 93 = 192$ bytes. Thus, for \mathcal{M} proof-of-contact messages, the user stores $(192\mathcal{M})$ bytes. However, with the signature aggregation technique, the user only stores one signature (σ_{agg}) instead of \mathcal{M} individual signatures. Thus, the storage overhead for \mathcal{M} proof-of-contact (or proof-of-visit) messages is $(136\mathcal{M} + 56)$ bytes.

2) **On-Chain Storage:** The Blockchain network in our system stores two ledgers for the COVID-19 status and the zones status. Each ledger consists of blocks, where each block has a header and a body. Based on the Raft consensus algorithm, the header of each block contains the hash of

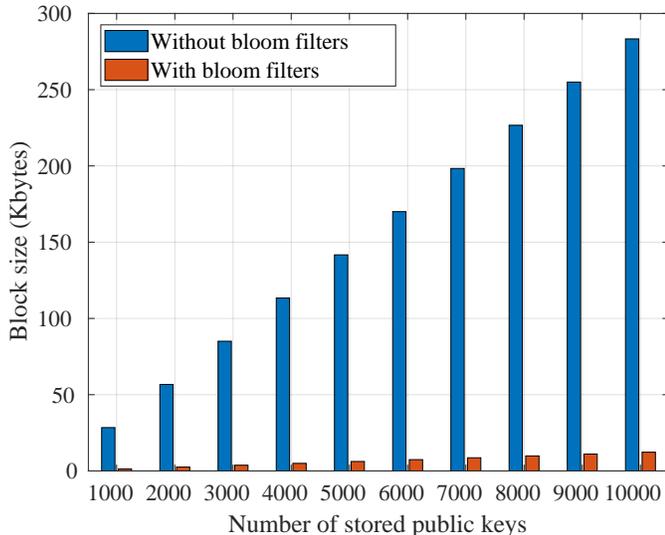


Fig. 9: The COVID-19 status ledger’s block size with and without using Bloom filters.

its previous block in the ledger, timestamp, and the leader’s signature. Thus, the block header is 100 bytes. In the COVID-19 status ledger, each block body has two Bloom filters, and in Section VI-B3, we found that to make the false positive probability very low, the filter size should equal to $10n$ bits, where n is the number of stored elements in the filter. Thus, the total size of the block in the COVID-19 status ledger is $(100 + (10N_1 + 10N_2)/8)$ bytes, where N_1 and N_2 are the number of infected and suspected users, respectively. In the zones status ledger, each block body has zones’ IDs, numbers of infected and suspected users in these zones, and zones’ status. Thus, the total size of the block in the zones status ledger is approximately $(100 + 6Z)$ bytes, where Z is the number of the zones.

To evaluate the reduction in the storage space due to using Bloom filters, in Fig. 9, we compare the block size of the COVID-19 status ledger with and without Bloom filters at different numbers of stored public keys ($N = N_1 + N_2$). The figure shows that the block size is significantly reduced by using the Bloom filter. For example, if the number of public keys stored in the block is 7000, the block size with Bloom filters is about 10 Kbytes, while it is about 200 Kbytes without Bloom filters. This indicates that *the use of Bloom filters results in about 95% reduction in the block size*. This is because without using Bloom filters, each public key needs 29 bytes storage space instead of just 10 bits if the Bloom filter is used.

VII. RELATED WORK

Since the outbreak of COVID-19 pandemic, several systems have been proposed in the literature to control the infection, especially through contact tracing. These systems can be categorized into centralized and decentralized based on the underlying architecture. In this section, we briefly explain these systems and discuss their limitations.

A. Centralized Systems

Most of the existing contact tracing systems are based on a centralized architecture [32], where a single central authority is responsible for identifying and notifying the close contacts of infected individuals.

Wan *et al.* [11] have proposed a contact tracing system, called ContactChaser, based on group signature cryptosystem. In ContactChaser, the health authority is the group manager that generates private keys for registered users. When two users encounter each other, they generate group signatures on the current time and location, and exchange these signatures with each other. If a user is tested positive for COVID-19, he/she uploads to the health authority all the signatures collected in the past 14 days. The authority identifies the close contacts by tracing the signers of the signatures. However, panic attacks can be launched because a user does not sign on the public key of the other user when they meet to prevent the authority from creating a social graph, and thus attackers can collect signatures issued for different users and claim that they are their close contacts. Another drawback is that the health authority can learn the locations visited by the users and their activities because it knows the real identity of the signer and the time and location of the contact are signed.

Altuwaiyan *et al.* [12] have proposed a contact tracing system, called EPIC, based on homomorphic encryption. The idea is that when a user visits a place, he/she collects messages from wireless devices in this place. If a user is infected, he/she sends the messages to a central server that enables non-infected users to learn whether they were close enough to an infected user. The system uses homomorphic encryption scheme to learn whether the users were close enough from each other. However, EPIC is vulnerable to tracking attack because the server can know the locations visited by the infected users due to including the hashed identifiers of the wireless devices located in each place. Also, EPIC is vulnerable to panic attack, where a malicious user can get identifiers of places that he/she did not visit and upload them to the server. Moreover, EPIC suffers from high computation, communication, and storage overheads due to using the inefficient homomorphic encryption scheme.

Jhanwar *et al.* [13] have proposed a contact tracing system, called PHyCT. In this system, each user generates a short-term secret seed. Then, the user computes two shares (broadcast share and authority share) from the seed using a 2-out-of-2 secret sharing algorithm. All seeds are kept locally in the user device. The user consistently uploads his/her identity encrypted with the secret seed, authority share, and hash of the broadcast share to a central authority database. When users encounter each other, they exchange broadcast shares. Once a user gets infected, he/she uploads all the secret seeds and collected messages to the central authority database to be used by other users to identify if they contacted the infected user. Close-contact users must report to the health department to be tested. For non-compliant users who have not reported to the health, the central authority reveals their identities by hashing the broadcast share obtained from the collected messages and searching for the corresponding entry. This makes PHyCT

TABLE IX: Comparison between our system and the existing infection control systems.

Comparison		ContactChaser [11]	EPIC [12]	PHyCT [13]	CAUDHT [14]	[15]	Our system
Privacy of infected users	Protection against Identification attack	✓	✓	✓	✓	×	✓
	Prevention of Social graph disclosure	✓	✓	×	✓	×	✓
	Protection against Tracking attack	✓	×	⊕	⊕	×	✓
Privacy of close contacts	Protection against Identification attack	✓	✓	✓	✓	×	✓
	Protection against Tracking attack	○	×	⊕	⊕	×	✓
Privacy of non-infected users	Protection against Identification attack	✓	✓	✓	✓	×	✓
	Protection against Tracking attack	✓	✓	⊕	⊕	×	✓
Prevention of False Reports		×	×	✓	✓	✓	✓
Tracing & Notification		✓	✓	✓	✓	✓	✓
Digital Pass		×	×	×	×	×	✓
Recommendation of safe Places		×	⊕	×	×	⊕	✓
Low storage usage		×	×	×	×	×	✓
Blockchain-based		×	×	×	×	✓	✓

Note: ✓: a realized feature, ×: an unrealized feature, ○: partially realized feature, and ⊕: not considered.

vulnerable to social graph disclosure because the authority can reveal the identities of both non-compliant and compliant users.

B. Decentralized Systems

Decentralized systems depend on a decentralized architecture using distributed hash table (DHT) or Blockchain, where multiple entities are responsible for identifying and notifying the close contacts of infected individuals.

Brack *et al.* [14] have proposed a contact tracing system, called CAUDHT. The idea is that when users encounter each other, they exchange temporary IDs. If a user is tested positive for COVID-19, he/she blinds his/her IDs used during the last 14 days and sends them to the health authority to sign as a proof of infection. Then, the infected user unblinds the signatures received from the health authority to obtain valid signatures on his/her IDs. To notify a close-contact user, the infected user computes a ciphertext by encrypting the signature on his/her ID used during the contact with the ID of the close-contact user. Then, the infected user creates a record on a distributed hash table (DHT) that consists of the close contact's ID and the ciphertext to notify the close contact user. However, this system suffers from a large storage overhead due to storing ciphertexts in the DHT.

Torky *et al.* [15] have proposed a Blockchain-based contact tracing system. The system consists of a Blockchain platform, mass-surveillance cameras, peer-to-peer (P2P) mobile application, and an infection verifier. Once a user is tested positive for COVID-19, a regular expression is created for him/her and recorded in the Blockchain platform. Then, the Blockchain submits a tracking request to mass-surveillance cameras monitoring the places visited by the user to identify his/her close contacts. The close contacts receive messages containing their infection instances via the P2P mobile application. A close contact user forwards the received infection instances to the infection verifier subsystem to verify it. However, this system is vulnerable to social graph disclosure and tracking due to using a mass-surveillance system. Also, mass-surveillance

systems are not available in many countries and it is costly to deploy a system for controlling COVID-19 infections.

C. Limitations and Contributions

The systems in [11]–[13] are centralized systems; thus, they suffer from the following issues. First, they are vulnerable to a single point of failure problem and DoS attack. Second, they lack transparency because the users have to trust a single central authority for performing the contact tracing without being able to validate the operations done by the server. On the other hand, very few decentralized contact tracing systems have been proposed [14], [15], but they suffer from several limitations. In Table IX, we compare our system to the existing works in terms of privacy and security features, infection control services, and performance metrics.

Our main contributions can be summarized as follows. First, compared to the existing systems, our system is the only one that preserves the privacy of the infected users and their close contacts against identification, social graph disclosure, and tracking attacks, while thwarting false reporting attacks. As explained earlier, although [15] utilizes the Blockchain, it is vulnerable to social graph disclosure and tracking due to using a mass-surveillance system. Also, mass-surveillance systems are not available in many countries and it is costly to deploy a system for controlling COVID-19 infections. Second, most of the existing systems focus only on contact tracing, which is not enough to control the infection. Our infection control system not only considers contact tracing, but also records the COVID-19 status of the system users to be used as a digital pass to prevent infected and suspected users from accessing public places to prevent spreading the virus by them. Moreover, our system categorizes zones according to their infection level so that users can avoid visiting highly contaminated zones to avoid contracting the virus. Finally, our system requires low computation and communication overheads and storage space. For instance, the system in [14] suffers from a large storage overhead because it needs to store ciphertexts for all the probable infected users in the system.

VIII. CONCLUSION

In this paper, we have proposed an efficient and privacy-preserving Blockchain-based infection control system. In our system, a group of health authorities form a consortium Blockchain to trace the close contacts of users who are tested positive for COVID-19. Compared to the existing systems, our system does not depend only on contact tracing to control the infection, but also on limiting the access of public places to non-infected users and recommending the safe-places to visit. We have performed security and privacy analysis to prove the security of our system and its ability to preserve the users' privacy against identification, social graph disclosure, and tracking attacks, while thwarting false reporting attacks. We have used the signature aggregation technique and the Bloom filters to enhance the scalability of our system. Extensive performance evaluations are conducted and the results demonstrate that the communication, computation, and storage overheads of our system are low.

REFERENCES

- [1] World Health Organization. (accessed: November 28, 2020) WHO coronavirus disease (COVID-19) dashboard. [Online]. Available: <https://covid19.who.int>
- [2] G. Onder, G. Rezza, and S. Brusaferro, "Case-fatality rate and characteristics of patients dying in relation to COVID-19 in Italy," *Jama*, vol. 323, no. 18, pp. 1775–1776, 2020.
- [3] R. P. Rajkumar, "COVID-19 and mental health: A review of the existing literature," *Asian journal of psychiatry*, p. 102066, 2020.
- [4] P. K. Ozili and T. Arun, "Spillover of COVID-19: impact on the global economy," *Available at SSRN 3562570*, 2020.
- [5] C. Zhan, W. Jiang, J. Li, H. Xu, and W. Sha, "Impact of COVID-19 lockdown on human activity and air quality in China," in *2020 IEEE International Symposium on Product Compliance Engineering-Asia (ISPCE-CN)*, 2020, pp. 1–5.
- [6] J. Yawney and S. A. Gadsden, "A study of the COVID-19 impacts on the Canadian population," *IEEE Access*, vol. 8, pp. 128 240–128 249, 2020.
- [7] V. Chamola, V. Hassija, V. Gupta, and M. Guizani, "A comprehensive review of the COVID-19 pandemic and the role of IoT, drones, AI, Blockchain, and 5G in managing its impact," *IEEE Access*, vol. 8, pp. 90 225–90 265, 2020.
- [8] Spiegel international. Germany increases coronavirus threat to "high". Accessed: September 5, 2020. [Online]. Available: <https://www.spiegel.de/international/germany/germany-increases-coronavirus-threat-to-high-a-a8fa63e2-2123-4c8c-aa73-f557244aaf07>
- [9] Tracetgether. Accessed: September 13, 2020. [Online]. Available: <https://www.tracetgether.gov.sg/>
- [10] Aarogya Setu. Accessed: September 13, 2020. [Online]. Available: <https://www.mygov.in/aarogya-setu-app/>
- [11] Z. Wan and X. Liu, "Contactchaser: a simple yet effective contact tracing scheme with strong privacy," Cryptology ePrint Archive, Report 2020/630, Tech. Rep., 2020.
- [12] T. Altuwaiyan, M. Hadian, and X. Liang, "EPIC: efficient privacy-preserving contact tracing for infection detection," in *2018 IEEE International Conference on Communications (ICC)*, 2018, pp. 1–6.
- [13] M. P. Jhanwar and S. Sarkar, "PHyCT: Privacy preserving hybrid contact tracing," Cryptology ePrint Archive, Report 2020/793, 2020. <https://eprint.iacr.org> . . . , Tech. Rep.
- [14] S. Brack, L. Reichert, and B. Scheuermann, "Decentralized contact tracing using a DHT and blind signatures," *IACR Cryptol. ePrint Arch.*, vol. 2020, p. 398, 2020.
- [15] M. Torky and A. E. Hassanien, "COVID-19 blockchain framework: innovative approach," *arXiv preprint arXiv:2004.06081*, 2020.
- [16] M. M. Arifeen, A. Al Mamun, M. S. Kaiser, and M. Mahmud, "Blockchain-enable contact tracing for preserving user privacy during COVID-19 outbreak," 2020.
- [17] L. Reichert, S. Brack, and B. Scheuermann, "Privacy-preserving contact tracing of COVID-19 patients," *IACR Cryptol. ePrint Arch.*, vol. 2020, p. 375, 2020.
- [18] C. Troncoso, M. Payer, J.-P. Hubaux, M. Salathé, J. Larus, E. Bugnion, W. Lueks, T. Stadler, A. Pyrgelis, D. Antonioli *et al.*, "Decentralized privacy-preserving proximity tracing," *arXiv preprint arXiv:2005.12273*, 2020.
- [19] J. Xie, H. Tang, T. Huang, F. R. Yu, R. Xie, J. Liu, and Y. Liu, "A survey of Blockchain technology applied to smart cities: Research issues and challenges," *IEEE Communications Surveys Tutorials*, vol. 21, no. 3, pp. 2794–2830, 2019.
- [20] M. M. Badr, W. Al Amiri, M. M. Fouda, M. M. Mahmoud, A. J. Aljohani, and W. Alasmay, "Smart parking system with privacy preservation and reputation management using Blockchain," *IEEE Access*, vol. 8, pp. 150 823–150 843, 2020.
- [21] Z. Zheng, S. Xie, H. Dai, X. Chen, and H. Wang, "An overview of Blockchain technology: Architecture, consensus, and future trends," in *Proc. of IEEE International Congress on Big Data (BigData Congress)*, Honolulu, HI, USA, 2017.
- [22] G.-T. Nguyen and K. Kim, "A survey about consensus algorithms used in Blockchain," *Journal of Information processing systems*, vol. 14, no. 1, 2018.
- [23] D. Ongaro and J. Ousterhout, "In search of an understandable consensus algorithm," in *USENIX Annual Technical Conference (USENIX ATC 14)*, pp. 305–319, 2014.
- [24] J. P. Morgan Chase. A permissioned implementation of Ethereum. [Online]. Available: <https://github.com/jpmorganchase/quorum>, 2018.
- [25] S. J. Alsunaidi and F. A. Alhaidari, "A survey of consensus algorithms for Blockchain technology," in *Proc. of International Conference on Computer and Information Sciences (ICCIS)*, Sakaka, Saudi Arabia, 2019.
- [26] A. Kumar, J. Xu, and J. Wang, "Space-code Bloom filter for efficient per-flow traffic measurement," *IEEE Journal on Selected Areas in Communications*, vol. 24, no. 12, pp. 2327–2339, 2006.
- [27] K. Rabieh, M. M. E. A. Mahmoud, K. Akkaya, and S. Tonyali, "Scalable certificate revocation schemes for smart grid AMI networks using Bloom filters," *IEEE Transactions on Dependable and Secure Computing*, vol. 14, no. 4, pp. 420–432, 2017.
- [28] Li Fan, Pei Cao, J. Almeida, and A. Z. Broder, "Summary cache: a scalable wide-area web cache sharing protocol," *IEEE/ACM Transactions on Networking*, vol. 8, no. 3, pp. 281–293, 2000.
- [29] D. Johnson, A. Menezes, and S. Vanstone, "The elliptic curve digital signature algorithm (ECDSA)," *International journal of information security*, vol. 1, no. 1, pp. 36–63, 2001.
- [30] J. W. Bos, J. A. Halderman, N. Heninger, J. Moore, M. Naehrig, and E. Wustrow, "Elliptic curve cryptography in practice," in *International Conference on Financial Cryptography and Data Security*. Springer, 2014, pp. 157–175.
- [31] J. A. Akinyele, C. Garman, I. Miers, M. W. Pagano, M. Rushanan, M. Green, and A. D. Rubin, "Charm: a framework for rapidly prototyping cryptosystems," *Journal of Cryptographic Engineering*, vol. 3, no. 2, pp. 111–128, 2013.
- [32] R. Sun, W. Wang, M. Xue, G. Tyson, S. Camtepe, and D. Ranasinghe, "Vetting security and privacy of global COVID-19 contact tracing applications," *arXiv preprint arXiv:2006.10933*, 2020.