Title	The Role of Blockchain to Fight Against COVID-19
Authors(s)	Kalla, Anshuman, Hewa, Tharaka, Mishra, Raaj Anand, Ylianttila, Mika, Liyanage, Madhusanka
Publication date	2020-09-01
Publication information	Kalla, Anshuman, Tharaka Hewa, Raaj Anand Mishra, Mika Ylianttila, and Madhusanka Liyanage. “The Role of Blockchain to Fight Against COVID-19.” IEEE, September 1, 2020. https://doi.org/10.1109/EMR.2020.3014052.
Publisher	IEEE
Item record/more information	http://hdl.handle.net/10197/11507
Publisher's statement	© 2020 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.
Publisher's version (DOI)	10.1109/EMR.2020.3014052

The Role of Blockchain to Fight Against COVID-19

Anshuman Kalla, *Member, IEEE,* Tharaka Hewa, *Student Member, IEEE,* Raaj Anand Mishra, *Student Member, IEEE,* Mika Ylianttila, *Senior Member, IEEE,* and Madhusanka Liyanage, *Member, IEEE*

***Index Terms*—COVID-19, SARS-CoV-2, Blockchain, DLT, Smart Contract, Pandemic**

***Abstract*—The COVID-19 pandemic has adversely affected almost all aspects of human life, various sectors of business, and regions of the world. The flow of human activities halted for several months, and are now being carefully redefined to align with guidelines and recommendations to avoid the spread of the novel coronavirus. In contrast to other pandemics the world has witnessed in the past, the technological advancements of the current era are a boon that can play a key role in safeguarding humanity. In this work, we begin by highlighting general challenges that have arisen during the COVID-19 pandemic. Next, to gauge the applicability of blockchain as a key enabling technology, we identify potential use cases to meet current needs. Further, for each use case, we present a high-level view of how blockchain can be leveraged and discuss the expected performance. Finally, we highlight the challenges that must be addressed to harness the full potential of blockchain technology and discuss plausible solutions.**

I. Introduction

The earth and its inhabitants are struggling with a new disease called Coronavirus Disease 2019 (COVID-19). It is caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), first identified in Wuhan in the Hubei province of China in December 2019. It caused thousands of deaths in mainland China. By 11 March 2020, the World Health Organization (WHO) declared COVID-19 a worldwide pandemic [1]. At the time of writing, more than 13.5 million cases and more than 584 thousand deaths have been reported in more than 188 countries and regions [2].

The unprecedented transmission of this virus has given rise to a multitude of challenges that are shaking the roots of current human civilization. Some of the most evident challenges are described in Table I. Countries that have imposed lockdowns and travel restriction are facing the challenge of restraining physical human interaction when socialising is so natural to human beings. Continuing the provision of essential services and ensuring a constant supply of medicines and healthcare equipment is becoming increasingly difficult. Many national and international organizations, as well as individuals, tend to offer financial support to support these needs, but major challenges are to ensure proper distribution and provide transparency to organizations and donors. Another major challenge is the fake infodemic (or "disinfodemic") of fake information that is exacerbating the pandemic. Tech giants and governmental regulatory bodies are encountering difficulty in recognizing and combating disinformation. These challenges are being witnessed by many countries which have been hit by COVID-19, and urgent efforts to resolve them are needed.

Technological advances are one of the key strengths of the current era that may help us overcome the challenges posed by COVID-19. Novel technologies—such as Artificial Intelligence (AI) & Machine Learning (ML), Internet of Things (IoT), Blockchain, robotics & Unmanned Aerial Vehicles (UAVs), 3D printing, nanotechnology & synthetic biology, 5G communications, cloud & edge computing and Big Data—can be leveraged to develop intelligent emergency management strategies for the COVID-19 pandemic.

Notably, blockchain has been identified by the European Parliamentary Research Service (EPRS) as one of the ten key technologies to fight COVID-19 [3]. Blockchain provides a decentralized computational service architecture that eradicates most of the limitations associated with centralized computing ecosystems. The blockchain is a collection of computing nodes that are connected in a peer-to-peer (P2P) manner and mutually verify transactions executed within the network. In the blockchain, each block cryptographically seals a set of transactions and is linked with the previous block to form a hash-based (cryptographic) chain of blocks. Figure 1 delineates the seven key features of blockchain technology vital for the fight against COVID-19.

The rest of the paper is organized as follows. Section II discusses the role of blockchain in combating the COVID-19 outbreak and illustrates a wide range of use cases and applications. Section III highlights the challenges associated with the use of blockchain in the context of the COVID-19 pandemic and presents plausible solutions to mitigate these challenges. Section IV concludes the paper.

II. Use-cases Applications and Service Opportunities via Blockchain for COVID-19

This section provides a high-level discussion of how blockchain can support numerous use cases pertinent to COVID-19 (as shown in Figure 2). Table II intends to reflect the expectations in terms of latency, transaction throughput, cost, suitable consensus mechanism, and potential blockchain platforms for successful realization of each use case.

A. Contact Tracing

SARS-CoV-2 has an average incubation period from infection to symptoms of approximately 5.5 days, and it is estimated

Anshuman Kalla is with School of Computing and Information Technology, Manipal University Jaipur, India. e-mail: anshuman.kalla@jaipur.manipal.edu

Raaj Anand Mishra is with School of Computing and Information Technology, Manipal University Jaipur, India. e-mail: raaj.169103057@muj.manipal.edu

Tharaka Hewa and Mika Ylianttila are with the Center for Wireless Communications, University of Oulu, Finland. e-mail: {firstname.lastname}@oulu.fi

Madhusanka Liyanage is with the School of Computer Science, University College Dublin, Ireland and the Center for Wireless Communications, University of Oulu, Finland. e-mail:madhusanka@ucd.ie

TABLE I
GENERAL CHALLENGES FACED DURING COVID-19 PANDEMIC

Challenges	**Description**	**Real-world Examples**
Social distancing	Social distancing is a method used to slow the spread of the disease and "flatten the curve" of new cases given there is no medicine or vaccine licensed for the treatment and prevention of COVID-19. However, most day-to-day activities, such as shopping, banking, education, transportation, and medical treatment require physical interaction. Besides, limiting physical interactions may lead to social isolation and adverse psychological effects.	A three-fold increase in psychological distress has been reported in the USA, with particularly severe effects among those aged 18–29 years [4]. In India, more than 80% of 662 people surveyed reported being distracted by COVID-19 [5].
Fake infodemic	The massive flow of fake information (aka "disinfodemic") can lead to harmful self-medication or prophylactic treatment (as updated by WHO), panic behaviour, stress-born diseases, and non-adherence to governmental policies like social distancing, movement restrictions, and restriction on working and shopping hours. Further, the development of prediction models and estimation on future demands based on such fake information will be meaningless. Current platforms and their underlying technologies cannot tackle this problem and it is becoming increasingly difficult to counter fake information.	Competition for higher ratings have led the media to disseminate information related to COVID-19 without fact-checking. In India, more than two-thirds of COVID-19-related information received by people is misinformation [6]. In particular, UNESCO has defined four key types and nine key themes of disinformation prevailing during COVID-19 [7].
Continuation of essential governmental services	Essential governmental services such as public utilities (water, electricity, sanitation, etc.), salary and pension payments, tax collection, registration of births, marriages and deaths, elections, and visa issuance are expected to be available at all times. However, the continuous delivery and governance of their operation has become increasingly challenging as citizens and the governmental workforce are in lockdown or under stay-home restrictions.	U.S. Citizenship and Immigration Services (USCIS) declared an extension of 60 days in providing responses to requests, which increased the fear among temporary immigrants [8]. Further, due to COVID-19, electoral issues have been reported in Ohio and Wisconsin because of the changes in dates and format of elections [8].
Real-time data sharing	Global data synchronization is an essential factor to combat the COVID-19 pandemic. Sharing important data such as the number of affected patients, active cases, critical cases, recovered patients, deaths, etc. must occur in real-time to create public awareness, to support immediate proactive action, and to predict future patterns. Nevertheless, since digital information is prone to security attacks, issues like mishandling the ownership of data, absence of ways to check for data tampering, use of centralized data store that represent a single point of attack, and insufficient transparency in exchange of data, are technical challenges to combat COVID-19.	As mentioned in [9], two data sets, a first set of 425 early cases in Wuhan, and a second set of a larger number of cases in Italy and Wuhan, are not in sync. They lead to different implications.
Distribution of funding and charity	Financial organizations, such as World Bank, International Monetary Fund (IMF), and the European Union (EU) are offering loans and grants to overcome the ongoing and post-COVID-19 economic crisis in many countries. Such funding should be distributed to those in need of assistance in a transparent manner. However, many countries are failing to do so because of corruption and lack of proper automated systems. Further, it seems likely that citizens may be more motivated to donate money if they can transparently view the end use of their donated money.	An example of lack of automated system is reported in [10]. That study reported huge amounts of donated funds and materials were available at the outset of the pandemic but could not reach health workers in a timely manner because Hubei's government initially channeled all donations via the local Red Cross, which had a limited staff.
Efficient supply of medicines and healthcare equipment	There is a huge demand for medical supplies and equipment such face masks, sanitizer, Personal Protective Equipment (PPE), ventilators, Polymerase Chain Reaction (PCR) testing kits and probes. Without proper supply chain management, these items will not reach the place where are they are needed in timely manner. Also, the vendors may hide the availability of essential item to artificially inflate prices. Moreover, the quality and origin of such items should be verified because of the possibility of counterfeit products.	India contributes more than 20% of the global supply of generic drugs, and more than 200 countries (including the USA, EU, South Africa, and Russia) rely on this supply [11]. Due to COVID-19, India has imposed restrictions on the export of 26 bulk drugs (Active Pharmaceutical Ingredients (APIs)), which together make up approximately 10% of India's overall export [12].
Education	The education sector, including schools, institutes and training organizations, is completely shut down in many parts of the world. This may have long-term effects. Though online modes of education have been adopted, there are numerous issues, including a technological inability to handle the sudden heavy data traffic, a lack of training for instructors in these modes of delivery, a lack of secure cross-collaborative platforms, and absence of many dimensions of effective teaching-learning methodology like body language, gestures, and real-time group discussion.	Security glitches and hacking issues have been reported for the use of Zoom video conferencing application [13]. Further, it has been reported that UK medical students, in the second-to-last year, are facing suspension in their clinical placements.
Food Distribution	The transportation and distribution of food has been hampered by lockdowns and movement restrictions. This situation is affecting both consumers and farmers: many people are experiencing hunger or even starvation due to the severe increase in unemployment, while at the same time, farmers are finding it difficult to sell their yields. Thus, there is a kind of "deadlock" in the agricultural sector.	The World Food Program (WFP) has reported a record 82% increase in the estimated number of people who will be acutely food insecure by the end of 2020 due to COVID-19 [14]. Because of various COVID-related restrictions, the WFP is finding it difficult to distribute the food that is available to the people who need it.

that a high percentage of cases are asymptomatic. Thus, it is vital to effectively and rapidly identify all social interactions that happened during this infectious incubation period to confine the spread of COVID-19. This is accomplished via contact tracing, which aims to monitor close contacts (i.e. individuals that come within the close proximity of an infected person for some set duration of time). Ideally, when a person is diagnosed with COVID-19, all of their close contacts would

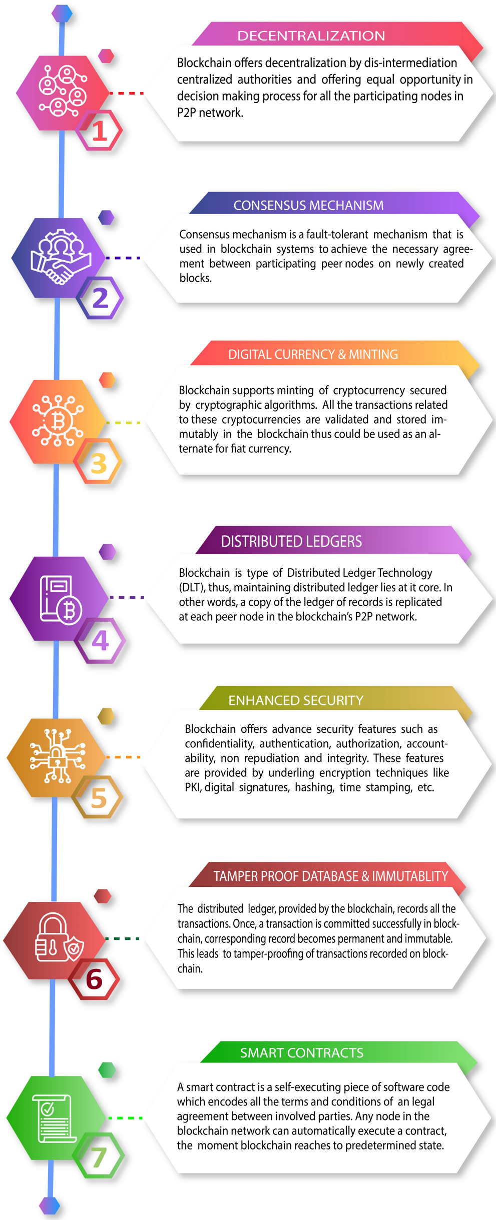

Fig. 1. Key Features of Blockchain that can use to Mitigate COVID-19 challenges

receive an alert and further instructions. Several contact tracing mobile applications have been developed using Bluetooth Low Energy (BLE) technology. Using BLE, it is possible to record close encounters between mobile phones, wearables and IoT devices. However, the biggest concerns with this method is how ensure data security and privacy for users. This because users' data gets stored and analyzed in a centralized cloud and thus users may loose the ownership of their data.

Blockchain is a viable alternative to address data security and privacy concerns. Instead of a centralized database, blockchain can offer a decentralized solution that allows users to retain full control of their data. Smart contracts can be established between patients and users to provide time-bound access to patients' data. Moreover, patients' privacy can be protected by enabling pseudo-anonymity. Instead of revealing the true identity of an infected person, the blockchain-based system can enable the use of a special digital fingerprint (public key or hash) for each patient.

B. Disaster Relief and Insurance

Nationwide lockdowns and social distancing rules have huge economic impacts on businesses around the world. Governments and financial organizations have the responsibility to help businesses by providing loans and other financial lifelines. However, using traditional paper-based procedures to help large number of businesses is going to be time consuming and ineffective. Therefore, fast, reliable and scalable solutions are sought by the helping agencies.

Blockchain with smart contracts can be used to simplify complicated application and approval processes for loans and insurance. The utilization of smart contacts as policy agreements can eliminate the inherent processing delays of traditional paper-based policies. Moreover, blockchain can remove third-party intermediaries. The benefits of such a system include faster processing time, lower cost, reduced operational risk, and more rapid settlement for all stakeholders involved.

C. Patient Information Sharing

Sharing relevant data among healthcare collaborators is of paramount importance when dealing with COVID-19 pandemic. Global data sharing among international research community would help to formulate powerful data sets which can play a fundamental role in COVID-19 research. These data-sharing mechanisms must take care to avoid violating national and international data-sharing regulations. Patients' privacy is the most important concern and is one of the impediments to the implementation of medical data sharing system as well as to its wide adoption. The national and international bodies enforce robust controls such as HIPAA and define data access control policies. Moreover, detailed patient information such as blood oxygen level, heart rates, and medication doses can be gathered by integrating with Medical IoT (MIoT) devices.

The decentralized storage offered by blockchain could greatly improve the security and privacy of healthcare data. Moreover, patients and hospitals can have increased control over their data due to the elimination of costly middleman in the form of centralized databases. In addition, blockchain could break the traditional silos of medical records and make the process of sharing between hospitals and medical professionals across the country and even around the world significantly easier. In fact, blockchain can enable real-time data sharing. Uploading MIoT data directly to a blockchain-based system can eliminate issues such as data forging and mutation. The additional transparency in collecting, storing and sharing data helps to build and maintain trust between stakeholders and protects patients' privacy.

D. Immigration and Emigration Procedures

The unprecedented global spread of COVID-19 has led many countries to shutdown all immigration checkpoints be it

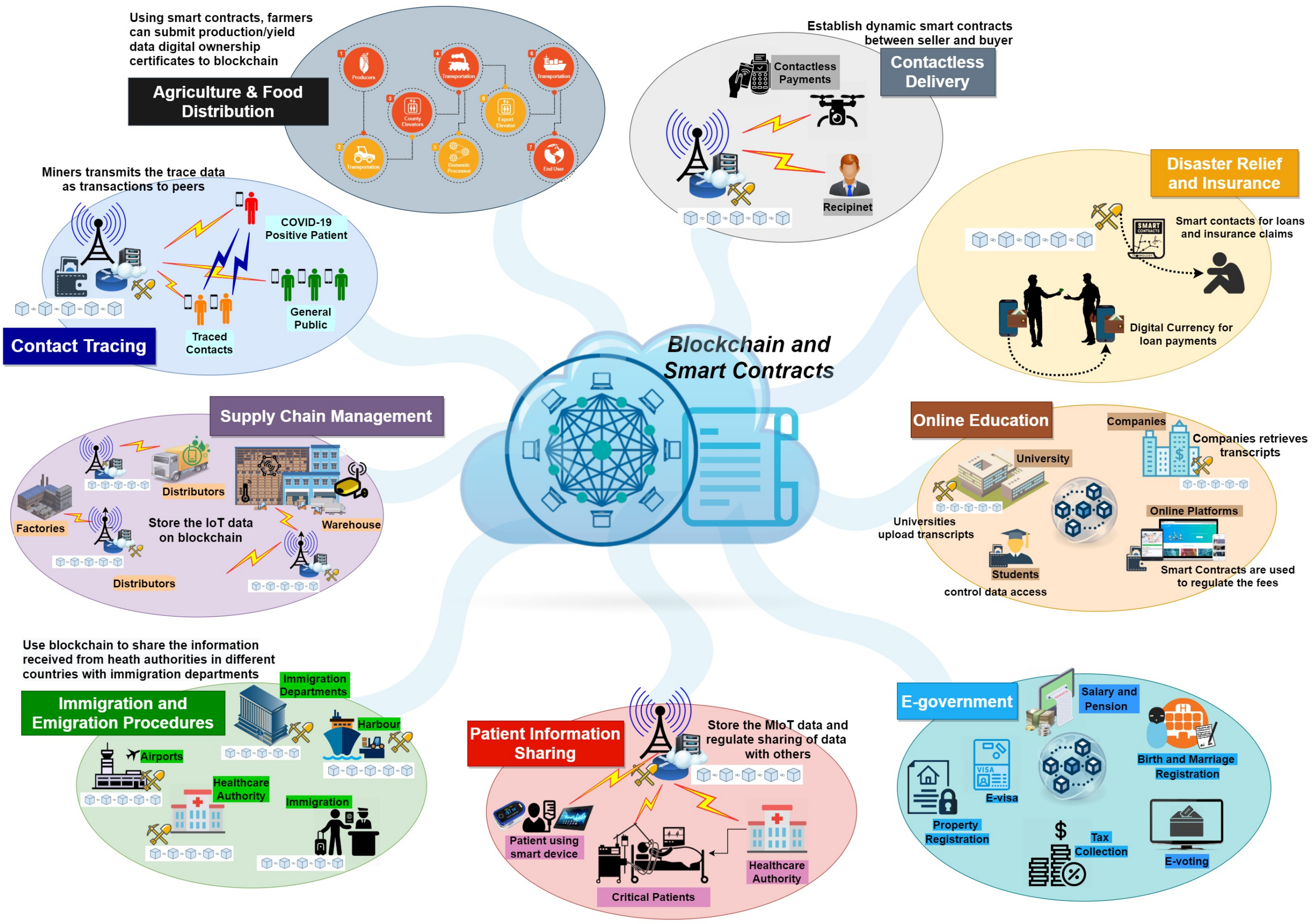

Fig. 2. Panoramic view of various Blockchain-enabled use cases to fight against COVID-19

airports, seaports, land-ports, rail-ports, or river-ports. Sooner or later, these restrictions will be either loosened or completely lifted. Thus, it is evident that both immigration and emigration will be critical in both the present and near-future. Various impediments are envisioned in this context, including the need for travelers to share medical history, travel history and real-time location in line with governments' policies. Moreover, such data will need to shared at the time of immigration checks when crossing international borders.

Blockchain-powered cross-country data sharing platforms can be established to handle immigration and emigration processes in a smarter way. Various integral features of blockchain systems with strict smart contracts, like immutability, access control, non-repudiation, auditability and provenance are vital for such applications. These salient features can pave the way for a secure, decentralized and collaborative immigration ecosystem. In the near future, we may see countries establishing consortium-type blockchain-based immigration systems that connect all immigration checkpoints. Such systems will have well-defined interoperability with similar systems in other countries.

E. Supply Chain Management

The world is witnessing severe supply chain disruptions due to the ongoing pandemic. Industrial production activities are at a standstill either because lockdown has been imposed or because factories are not equipped and/or designed to follow the new paradigm of social distancing and working with minimum physical contact. Further, import and export bans have affected the global supply chain. At present, it is difficult to analyze the exact level of disruption COVID-19 has caused in the global supply chain; regardless, it has resulted in serious crises in supply and demand. Depending on the type of good, there is either high demand or high supply. Panic-buying has resulted in a surge in demand for household essentials. Similarly, medical equipment and pharmaceutical supply chains are finding it difficult to keep the entire chain intact and meet the high demand.

Blockchain technology can play a pivotal role in building a more resilient supply chain. Blockchain can anonymously knit together all stakeholders, establishing a trust-less environment. Immutable recording of data logs supports auditability, provenance, and transparency, while well-designed smart contracts provide a high level of access restrictions and automation. For this particular use case, we are likely to see a mix of consortium and public blockchain systems.

TABLE II
SUMMARY OF EXPECTED PERFORMANCE AND EXISTING IMPLEMENTATIONS FOR BLOCKCHAIN ENABLED USE CASES [15]–[19]

Use-case	Type of Blockchain	Consensus Mechanism	Expected latency	Expected scalability	Transaction Cost	BC Platform
Contact Tracing	Public	PoW/PoS	Within hours	360-1440 transactions per phone per day	0 - 0.01 USD	Ethereum/Nexus
	Consoritum	Majority voting/DBFT			No cost	Hyperledger Fabric, SKUChain, NEO
Disaster Relief Insurance	Consortium	PoW/PoS	Within days	10 - 100,000 transactions per institute per day	0 - 1 USD	Ethereum, Bitcoin
	Private	BFT/ RAFT			No cost	R3 Corda, Hyperledger Fabric
Patient Information Sharing	Consoritum	PoW/PoS	Within seconds	1000- 100,000 transactions per minute	< 0.01 USD per transaction	Ethereum, MedicalChain
	Private	Proof of Interoparability CBFT			No cost	Private Ethereum/ Hyperledger Iroha
Immigration and Emigration Procedures	Consoritum	PoW/PoS	Within seconds	1000- 1 million per border per day	< 0 - 0.05 USD per transaction	Ethereum
	Private	BFT			No cost	Hyperledger Fabric
Supply Chain Management	Consoritum	PoW/PoS	Within minutes	100- 10,000 per system per day	0 - 0.01 USD per transaction	Ethereum
	Private	BFT			No cost	Hyperledger Fabric/NEO
Automated Surveillance and Contactless Delivery	Public	PoW/PoS	Within seconds	100- 100,000 per municipality per day	0 - 0.01 USD per transaction	Ethereum
	Private	BFT			No cost	Hyperledger Fabric
Online Education and Secure Certification	Public	PoW/PoS/PoA	Within hours	100 - 10,000 per municipality per day	0 - 0.01 USD per transaction	Ethereum, Apla
	Private	BFT			No cost	Hyperledger Fabric
Manufacturing Management	Public	PoW/PoS	Within seconds	1000 - 1 million per factory per day	0 - 0.01 USD per transaction	Ethereum
	Private	BFT			No cost	Hyperledger Fabric
E-Government	Consortium	PoW/PoS/PoA	Within days	100- 10,000 per municipality per day	0 - 1 USD per transaction	Ethereum, Apla
	Private	BFT			No cost	Hyperledger Fabric
Agriculture	Consortium	PoW/PoS/PoA	Within seconds	100- 100,000 per regio per day	0 - 1 USD per transaction	Ethereum, Apla
	Private	BFT			No cost	Hyperledger Fabric
Food distribution	Consortium	PoW/PoS/PoA	Within seconds	100- 10,000 per municipality per day	0 - 1 USD per transaction	Ethereum, Apla
	Private	BFT			No cost	Hyperledger Fabric

Proof of Work (PoW), Proof of Authority (PoA), Proof of Stake (PoS) and Practical Byzantine Fault Tolerance (PBFT), United States Dollar (USD), Delegated Byzantine Fault Tolerence(DBFT), Chain-based Byzantine Fault Tolerant(CBFT)

F. Automated Surveillance & Contactless Delivery

For now, the only way to defeat the COVID-19 pandemic is to cultivate habits such as social distancing, minimal touching, wearing facemasks, and self-tracking symptoms like fever, coughing, and difficulty in breathing. However, adopting these behaviors seems to be challenging, especially since they do not align with the natural behaviors of human beings. This disconnect implies that a certain level of continuous and automated surveillance is required for alerts to save countless lives. Further, the current situation demands contactless (robotic) delivery of essential supplies (food, medicine, etc.) to people under lockdown, especially in areas with very high transmission rates, where sending a person for doorstep delivery might not be feasible.

Blockchain-powered UAVs and robots are well-suited to support this use case. Increasing use of UAVs have already been seen, with many countries are using them for public announcements, surveillance, testing for symptoms (like temperature) and contactless delivery. Though UAVs have the unique ability to precisely maneuver and perform task without human intervention, they are prone to security attacks. Such attacks may change the intended function and/or allow data theft. Blockchain, along with smart contracts designed in accordance with governmental or healthcare policies, can empower UAVs to function securely, provide restricted access to captured data, integrate digital payment systems, etc.

G. Online Education & Secure Certification

Many countries have closed their schools and universities for an extended period. Nonetheless, the on-going situation should not cease the process of imparting education which is indispensable for individual growth and ultimately drives the growth of a nation. Online education has become the most viable route forward; but systems for online education are not well established and are facing many challenges. These include a lack of secure tracking (logs) of learning process, the threat of data theft (for students and instructors), poor cross-platform collaboration, and difficulty in verifying the authenticity of students' credentials (degree, transcripts, and other certificates).

Blockchain-based online education platforms can offer a wide range of possibilities to mitigate these issues. For instance, such systems enable secure cross-platform sharing of online content and encourage automatic standardization across educational establishments. Smart contracts and tokens can be used to device correct payment system based on the exact usage of content. Decentralized blockchain-based storage increases the security of student data while ensuring it remains available to the authorized users. Finally, blockchain allows fast, efficient and secure issuance and sharing of verifiable educational credentials. Once the issuing authority of an institute uploads a credential to a blockchain-based system, the entitled student gets the full control of the credential. Students can then provide further viewing access to recruiters, professors or universities, as they choose.

H. Manufacturing Management

The demand for key commodities such as sanitizers, face masks, test swabs, PPE, and disinfectants has surged with COVID-19. To meet the demand, many companies have to outsource their production to third parties because they lack sufficient production capabilities. This gives rise to serious concern, as these third parties may not fulfil quality standards or meet guidelines for hygienic compliance. Most importantly, COVID-19 medicines and vaccines will become significant commodities in the near future. Many small plants and micro-manufacturing sites will be required to operate simultaneously and collaboratively to satisfy global demand. In view of the exponential increase in COVID-19 cases, establishing time-consuming paper-based traditional collaborations may not be feasible. Thus, an integrated, robust, collaborative compliance control monitoring framework is required to ease and govern the manufacturing process.

Blockchain-enabled IoT systems can be used to validate the integrity of production. With IoT, quality measurements can be obtained at different stages of production: gathering raw materials, manufacturing, storing, transporting, etc. Blockchain nodes can be deployed in factories to connect with their master production line. Thus, blockchain-integrated IoT systems enable secure logging of production data in an immutable and decentralized manner. Further, smart contracts can hold the logic required to conduct audits to monitor non-compliance rates. Future COVID-19 vaccines and medicines could be globally manufactured using blockchain-enabled cloud controlled manufacturing ecosystems. Smart contracts could be utilized to manage the royalties and other intellectual property rights in such decentralized production environments.

I. E-government

E-government, or digital government, refers to the substantial use of Information and Communications Technology (ICT) to support the provision of public and government services provided to a country's citizens. These services include essential public utilities (water, gas, electricity, sanitation, etc.), salary payment, tax collection, marriage and divorce services, land registration, elections, visa processing, and so on. The e-government concept proposes to digitize all or some parts of these services.

The use of blockchain for e-government can ensure security by enhancing integrity, immutability, confidentiality and data consistency between organisations. Moreover, its use improves efficiency by reducing processing delays and lowering operational costs. The key features of blockchain, such as notarization, shared database and workflow automation, are useful when implementing different operational features in e-government systems. Such systems can automatically detect spot for possible errors and counterfeiting attempts.

J. Agriculture and Food Distribution

Agriculture and food distribution is essential for human life and must continue to run smoothly. However, strict disease control measures, like travel bans, export restrictions, closure of informal labor sectors, shutdown of local markets, etc. have resulted in numerous challenges for farmers, suppliers, producers, distributors, retailers and consumers. Farmers are finding it difficult to sell their yield at a good price, since producers are not able to run their facilities at full capacity. Distributors are finding it difficult to cross state and country borders because of the time required to seek official permission. Moreover, because of COVID-19, organizations providing humanitarian services, like the WFP, are experiencing a severe financial crisis as well as difficulty in keeping their food distribution cycle intact [14].

In this context, blockchain can provide pragmatic solutions with agility. Smart contract-based automation can replace paper-based and lengthy agreements with a trustless digital market, where buying and selling can be quick without compromising ownership. Since blockchain allows two parties to transact directly, producers can procure raw material directly from farmers. This would help farmers get better prices for their produce, and reduce the overall price of food products. Leveraging blockchain technology, international or national humanitarian organizations can remotely and securely help needy people buy free or subsidized food from local vendors [14]. Further, more donors may tend to donate to good causes, since blockchain-based systems provide transparency as well as anonymity.

III. Integration Challenges and Possible Solutions

Blockchain technology has enormous potential to help in the current pandemic. Nevertheless, there are some challenges which must be addressed to embrace blockchain technology and leverage maximum benefit. This section aims to present these challenges and provide a landscape of possible solutions. Table III summarizes the specific advantages that blockchain introduces for every use case and lists the corresponding challenges.

A. Legal disputes

Hitherto, enforcement of commercial and business laws have carried the implicit assumption that every organization has a hierarchical structure with a central authority that owns the responsibility [20]. The central position or entity of each organization is responsible for its overall smooth functioning and is liable for any legal issues. In contrast, since blockchain allows decentralization, anonymity, and automation, the challenge is determining *Who bears the ownership, in terms of legal liability, when decentralized automation with anonymity is provided by blockchain [20]?* In the case of any legal dispute or any discrepancy, especially regarding public blockchain infrastructure, *which jurisdiction will apply?* If a smart contract is found to be erroneous, then *who owns the responsibility?*

Possible Solutions: For fruitful emergence and wide adaptation of blockchain-based innovative services and use cases, courts and legal systems need to develop a new legal framework and corresponding administrative processes. Such efforts would allow smooth integration of blockchain technology with public/governmental institutes. Blockchain technology does not completely replace existing public services—it adds to them and makes them more efficient.

B. Privacy Requirements

Blockchain immutably records data in a distributed way such that all the nodes (i.e., miners) are in possession of the entire database. This gives rise to privacy issues that are related to the confidentiality, control and management of data [21], which can be users' personal data or perhaps a trade secrets of an organization. Depending on the type of blockchain (along with the sort of cryptographic or encryption mechanisms) being employed, there may be different methods for data processing and storage, as well as viewing, which in turn lead to different levels of security vulnerabilities and non-compliance with privacy laws (the EU's GDPR, Brazil's LGPD, California's CCPA, etc.). Thus, interesting questions include: *Which type of blockchain should be used for which domain of application? If the mining nodes are spread across continents and countries, which privacy laws will apply? Is this decided based on the location of the miner that mined a new block? If so, then should the privacy laws be part of blockchain operations to control where mining should take place?*

Possible Solutions: To make blockchain technology a profitable venture for organizations/companies that are apprehensive about its use, private data should be stored off-chain. Though centralized off-chain storage can be used, it is better to use distributed off-chain storage to ensure both the availability and privacy of data. Moreover, depending on the application scenario, another level/layer of security may be employed to make off-chain storage privacy protected. New privacy methods, such as privacy-by-design and mixing, and Privacy Enhancing Technologies (PETs) such as homomorphic encryption, Attribute-Based Encryption (ABE), zero-knowledge proof, non-interactive zero-knowledge proof, format-preserving encryption, secure multi-party computation and obfuscation can be utilized to enhance privacy.

C. Security Issues

Blockchain is a powerful combination of many technologies—P2P networking, distributed ledger, consensus mechanism, and cryptographic techniques—and thus offers strong security. Nevertheless, there are numerous kinds of attack that can be mounted on blockchain applications via wallet hijacking, crypto-stealing malware and transaction likability. Such attacks are becoming increasingly popular because they are easy to deploy since they do not directly deal with secure blockchain infrastructure. These attacks aim to alter information related to transactions at the entry-point itself such that incorrect and malicious transaction is immutably confirmed on the blockchain [20]. Further, with advancements in technologies like quantum computing, attacks to alter the blockchain may become possible. In the future, when quantum computing proves its supremacy over high-end Application Specific Integrated Circuit (ASIC) computing, blockchain will have to be either redesigned or incrementally upgraded. Thus, challenging questions are: *Is blockchain technology secure and future-ready? If blockchain design principles need to be reinvented in the future, how can existing data be migrated?*

Possible Solutions: Better encryption techniques are to be designed to ensure strong security. For instance, the use of homomorphic signature has been shown to work better than public-key certificates [22]. A system based on hybrid blockchain can be used to justify the different level of security; however, one must be extra cautious at points of intersection. The security of smart contacts can be improved by using a Trusted Execution Environment (TEE) and game-based smart contracts.

D. Latency, Throughput and Scalability

Latency is the time after a transaction is sent until it is confirmed by the blockchain infrastructure. Much of blockchain latency is ascribed to the time required to mine a new block. Depending on the type of blockchain and the specification of the platform used, there can be variation in the latency experienced. Currently, latency can be anywhere from tens of seconds to tens of minutes. The result of high latency is lower transaction throughput (i.e. fewer transactions per unit time), which gives rise to scalability issues. The challenging questions are: *Can blockchain perform thousands of transactions per second when performed by existing mechanisms? Will scalability come at the cost of security?*

Possible Solutions: To improve transaction throughput and make blockchain scalable, researchers are working on innovative solutions, like sharding [23] and layer-2 scalability solutions [24]. Sharding is a way to achieve network-wide scalability such that a rapidly growing blockchain network can be logically divided into groups, called shards. Each node then can be mapped to one or more shards and will thus process and store selected transactions. Recently, a Directed Acyclic Graph (DAG) approach has been also proposed to improve transaction throughput [25]. The design of alternative application-specific consensus algorithms and hierarchical blockchain systems can further improve the latency, throughput and scalability of such systems.

TABLE III
ROLE OF BLOCKCHAIN AND PERTINENT CHALLENGES FOR IDENTIFIED USE CASES

Use Cases	Blockchain based Solution	Advantages of using blockchain										Blockchain related Deployment Challenges
		Decentralization	**Provenance**	**Non-Repudiation**	**Anonymity**	**Immutability**	**Availability**	**Auditability**	**Automation**	**Lower Cost**	**Confidentiality**	
Contact Tracing	Use of blockchain-based decentralized application for contact tracing ensures security and can allow users to retain ownership of data.	✓	-	-	✓	✓	✓	✓	✓	-	✓	Compliance to privacy laws, throughput, scalability, and voluminous data management
Disaster Relief and Insurance	Blockchain can enable creation of decentralized automated financial system which can motivate donors and generate confidence in insurance sector.	✓	✓	✓	-	✓	-	✓	✓	✓	✓	Secure designing of smart contracts, security attacks external to blockchain, and area of jurisdiction for legal disputes
Patient Information Sharing	Blockchain can empower the development of trusted global healthcare platform which allows secure data sharing among medical collaborators, yet protects the privacy.	✓	✓	✓	✓	✓	✓	-	✓	✓	✓	Interoperability, security and privacy (confidentiality and access control), data storage, light-weight and operationally inexpensive
Immigration and emigration procedures	Blockchain-based national and international collaborative and decentralized immigration ecosystem can provide a way to confine the transmission.	✓	✓	✓	-	✓	✓	✓	✓	-	✓	Interoperability, privacy laws, latency, modifications in smart contract as per changes in governmental policies of a country
Supply chain management	Underpinning of blockchain can help in realization of resilient, automated, and trust-less supply chain management system.	✓	✓	✓	-	✓	✓	✓	✓	✓	-	Data management (both relevant and obsolete data), latency, and scalability.
Automated Surveillance & Contactless Delivery	Blockchain powered UAVs and robots are best solution to automate secure surveillance and contactless delivery of medicines and food items.	✓	-	✓	-	✓	-	✓	✓	✓	✓	Physical as well as security attacks, privacy invasion, legal issues in case of accidents, light-weight consensus algorithms for resource-constrained robots
Online Education	Blockchain-based online educational platforms can revolutionize the way education is imparted online and globally verifiable certificates are issued.	✓	✓	✓	-	✓	✓	✓	✓	✓	✓	Operational cost of transaction, throughput, data storage, number of simultaneous users, and certificate revoking
Manufacturing Management	Blockchain can support the development of integrated trust-less collaborative and compliance control monitoring system for production and manufacturing.	✓	✓	✓	-	✓	✓	✓	✓	✓	-	Dealing with voluminous data and old obsolete data, security attacks, legal issues and settlements, interoperability among collaborators
E-government	Blockchain among other ICT technologies, can nurture realization of secure and decentralized e-government that can better facilitate citizens of country	✓	✓	✓	-	✓	✓	✓	✓	✓	✓	Legal issues, updating smart contracts which amendments in laws, defining laws for decentralized systems, massive data storage
Agriculture & Food distribution	Blockchain based trustless digital market can offer pragmatic solution to buying, selling and distribution of food. Also, it ensures transparency with anonymity to the stakeholders like donors, distributing agencies, bulk food sellers, and needy recipients.	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Integration and interoperability challenges with the existing systems, massive volume of data storage requirements, ensuring compliance with governmental policies

E. Resource Utilization

Blockchain technology is (hyper) resource-intensive due to the inherent transaction validation process, which incentivizes the mining process and distributed storage. The economic incentive, in the form of rewards for mining a new block, has paved the way for a dense global web of mining farms utilizing high end application-specific processors. These mining farms require massive energy input to run, which inevitably has some adverse environmental effects. In this context, some of the challenging questions are: *How can a light-weight more energy-efficient blockchain be built? How can renewable energy sources be used to supply the energy required for* *blockchain mining farms? How can the heat dissipated by mining farms be reused such that cost of mining is reduced and impact on the environment is minimized?*

Possible Solutions: To promote and ease the use of blockchain technology, dedicated cross-community and collaborative research will be required to innovate light-weight cryptographic algorithms. These algorithms must be secure and resilient to futuristic quantum computing-based attacks while remaining computationally inexpensive. Moreover, a new application-specific consensus algorithm will be required with the roll-out of 5G enabled IoT applications.

IV. Conclusion

The COVID-19 pandemic has affected many sectors of life, including healthcare, finance, politics, economics, and education. Blockchain can play a vital role in the management of the post-COVID-19 world. The key features of blockchain can support proper implementation of many use cases, such as contact tracing, disaster relief, patient information sharing, e-government, supply chain management, online education, immigration management, manufacturing management, automated surveillance and contact-less delivery. However, a variety of challenges, such as legal, security, privacy, latency, throughput, scalability and resource utilization issues must be resolved before blockchain can be fully utilized for these purposes.

Acknowledgement

This work is partly supported by European Union in RESPONSE 5G (Grant No: 789658), Academy of Finland in 6Genesis (grant no. 318927) and Secure Connect projects.

References

[1] WHO Director-General's opening remarks at the media briefing on COVID-19 - 11 March 2020. WHO. (accessed on 07.06.2020). [Online]. Available: https://www.who.int/dg/speeches/detail/who-director-general-s-opening-remarks-at-the-media-briefing-on-covid-19---11-march-2020

[2] COVID-19 Dashboard. The Center for Systems Science and Engineering (CSSE) at Johns Hopkins University (JHU). Accessed on 16.07.2020. [Online]. Available: https://coronavirus.jhu.edu/map.html

[3] M. Kritikos. Ten technologies to fight coronavirus. European Parliamentary Research Service (ERPS). Accessed on 04.06.2020. [Online]. Available: http://www.europarl.europa.eu/RegData/etudes/IDAN/2020/641543/EPRS_IDA(2020)641543_EN.pdf

[4] E. E. McGinty, R. Presskreischer, H. Han, and C. L. Barry, "Psychological distress and loneliness reported by us adults in 2018 and april 2020," *JAMA*, 2020.

[5] D. Roy, S. Tripathy, S. K. Kar, N. Sharma, S. K. Verma, and V. Kaushal, "Study of knowledge, attitude, anxiety & perceived mental healthcare need in indian population during covid-19 pandemic," *Asian Journal of Psychiatry*, p. 102083, 2020.

[6] R. Datta, A. Yadav, A. Singh, K. Datta, and A. Bansal, "The infodemics of covid-19 amongst healthcare professionals in india," *Medical Journal Armed Forces India*, 2020.

[7] J. Posetti and K. Bontcheva, "Disinfodemic deciphering covid-19 disinformation," UNESCO, accessed on 06.06.2020. [Online]. Available: https://en.unesco.org/sites/default/files/disinfodemic_deciphering_covid19_disinformation.pdf

[8] K. Pistor, "Law in the time of covid-19," 2020.

[9] C. J. Galvin, L. Fernandez-Luque, and Y.-C. J. Li, "Accelerating the global response against the exponentially growing covid-19 outbreak through decent data sharing," *Diagnostic Microbiology and Infectious Disease*, p. 115070, 2020.

[10] K. Yang, "Unprecedented challenges, familiar paradoxes: Covid-19 and governance in a new normal state of risks," *Public Administration Review*.

[11] "Annual report 2019-20," Ministry of Chemicals and Fertilizers, Department of Pharmaceuticals, accessed on 06.06.2020. [Online]. Available: https://pharmaceuticals.gov.in/sites/default/files/Annual\%20Report\%202019-20.pdf

[12] P. J. Guerin, S. Singh-Phulgenda, and N. Strub-Wourgaft, "The consequence of covid-19 on the global supply of medical products: Why indian generics matter for the world?" *F1000Research*, vol. 9, no. 225, p. 225, 2020.

[13] A. Aiken, "Zooming in on privacy concerns," *Index on Censorship*, vol. 49, no. 2, pp. 24–27, 2020. [Online]. Available: https://doi.org/10.1177/0306422020935792

[14] COVID-19 LEVEL 3 EMERGENCY, External Situation Report #10. World Food Program. Accessed on 18.07.2020. [Online]. Available: https://docs.wfp.org/api/documents/796f66c15f6b46c38c9133d7c563a4c7/download/?_ga=2.118166731.33719838.1595050917-2106389774.1595050917

[15] L. Ferretti, C. Wymant, M. Kendall, L. Zhao, A. Nurtay, L. Abeler-Dörner, M. Parker, D. Bonsall, and C. Fraser, "Quantifying sars-cov-2 transmission suggests epidemic control with digital contact tracing," *Science*, vol. 368, no. 6491, 2020.

[16] S. J. Divey, M. H. Hekimoğlu, and T. Ravichandran, "Blockchains in Supply Chains: Potential Research Directions," in *2019 IEEE Technology & Engineering Management Conference (TEMSCON)*. IEEE, 2019, pp. 1–6.

[17] A. S. Yeole and D. Kalbande, "Use of internet of things (iot) in healthcare: A survey," in *Proceedings of the ACM Symposium on Women in Research 2016*, 2016, pp. 71–76.

[18] B. Flynn, M. Pagell, and B. Fugate, "Survey research design in supply chain management: the need for evolution in our expectations," *Journal of Supply Chain Management*, vol. 54, no. 1, pp. 1–15, 2018.

[19] C. Perera, C. H. Liu, and S. Jayawardena, "The emerging internet of things marketplace from an industrial perspective: A survey," *IEEE Transactions on Emerging Topics in Computing*, vol. 3, no. 4, pp. 585–598, 2015.

[20] J. Salmon and G. Myers, "Blockchain and associated legal issues for emerging markets," *International Finance Corporation, Washington, DC*, 2019.

[21] J. B. Bernabe, J. L. Canovas, J. L. Hernandez-Ramos, R. T. Moreno, and A. Skarmeta, "Privacy-preserving solutions for blockchain: review and challenges," *IEEE Access*, vol. 7, pp. 164 908–164 940, 2019.

[22] Q. Lin, H. Yan, Z. Huang, W. Chen, J. Shen, and Y. Tang, "An id-based linearly homomorphic signature scheme and its application in blockchain," *IEEE Access*, vol. 6, pp. 20 632–20 640, 2018.

[23] G. Yu, X. Wang, K. Yu, W. Ni, J. A. Zhang, and R. P. Liu, "Survey: Sharding in blockchains," *IEEE Access*, vol. 8, pp. 14 155–14 181, 2020.

[24] M. Jourenko, K. Kurazumi, M. Larangeira, and K. Tanaka, "Sok: A taxonomy for layer-2 scalability related protocols for cryptocurrencies." *IACR Cryptology ePrint Archive*, vol. 2019, p. 352, 2019.

[25] I. Kotilevets, I. Ivanova, I. Romanov, S. Magomedov, V. Nikonov, and S. Pavelev, "Implementation of directed acyclic graph in blockchain network to improve security and speed of transactions," *IFAC-PapersOnLine*, vol. 51, no. 30, pp. 693–696, 2018.

Anshuman Kalla is working as Associate Professor at the Department of Computer and Communication Engineering, School of Computing and Information Technology, Manipal University Jaipur, India. His research interests include Blockchain, ICN, IoT and networking. For More info: https://sites.google.com/site/kallanshuman/

Tharaka Hewa is a Doctoral student at the Centre for Wireless Communication, University of Oulu. His research interests include Blockchain, IoT, PKI and data privacy in healthcare systems.

Raaj Anand Mishra is an engineering student at the Department of Computer and Communication Engineering, School of Computing and Information Technology, Manipal University Jaipur, India. His research interests include Blockchain and Networking.

Mika Ylianttila (M. Sc, Dr.Sc, eMBA) is a full-time associate professor (tenure track) at the Centre for Wireless Communications (CWC), University of Oulu, Finland. His research interests include edge computing, network security, network virtualization and software-defined networking.

Madhusanka Liyanage is an Assistant Professor/Ad Astra Fellow at School of Computer Science, University College Dublin, Ireland. He is also an adjunct professor/docent at the University of Oulu, Finland. His research interests are SDN, IoT, Blockchains, MEC, mobile and network security. More info: http://www.madhusanka.com.