Blockchain-Enabled Telehealth Services Using Smart Contracts

HAYA R. HASAN1, KHALED SALAH1, (Senior Member, IEEE), RAJA JAYARAMAN2, IBRAR YAQOOB1, (Senior Member, IEEE), MOHAMMED OMAR2, AND SAMER ELLAHHAM3

1Department of Electrical Engineering and Computer Science, Khalifa University of Science and Technology, Abu Dhabi, United Arab Emirates
2Department of Industrial and Systems Engineering, Khalifa University of Science and Technology, Abu Dhabi, United Arab Emirates
3Heart and Vascular Institute, Cleveland Clinic Abu Dhabi, Abu Dhabi, United Arab Emirates

Corresponding author: Ibrar Yaqoob (ibrar.yaqoob@ku.ac.ae)

This publication is based on work supported by the Khalifa University of Science and Technology under Awards No. CIRA-2019-001 and RCII-2019-002-Center for Digital Supply Chain and Operations Management.

ABSTRACT Telehealth has gained a huge traction during the Coronavirus (COVID-19) pandemic. Telehealth enables physicians and medical care providers to remotely care for patients and monitor their symptoms. Today’s telehealth systems fall short in providing transparent, immutable, traceable, auditable, secure, and trustworthy services. In addition, they are centralized and subject to the single point of control and failure. In this paper, we propose a private blockchain-based solution to overcome the aforementioned challenges. We demonstrate how specifically three important telehealth services; namely, teleconsultation, drug administration, and medical testing can be enhanced using blockchain technology. Our proposed solution also ensures integrity, immutability, accountability, and non-repudiation for telehealth transactions initiated by multiple actors. For storing and keeping track of large-size digital content, such as images and audio and video recordings of telehealth service sessions, our proposed solution is integrated with off-chain storage systems including cloud storage or a decentralized storage system as that of the Interplanetary File System (IPFS). The registered participants are provided with access privileges based on their roles to ensure that restrictions are enforced on-chain. Smart contracts are developed to maintain data provenance and generate reliable alerts and notifications. The implementation and testing details of the algorithms are presented. We discuss, compare, and analyze the security features of our solution.

INDEX TERMS Telehealth, telemedicine, COVID-19, blockchain, Ethereum smart contracts, security, traceability.

I. INTRODUCTION

The Coronavirus (COVID-19) outbreak has begun in late 2019. It is confronting and challenging the existing healthcare systems. Recently, many doctors living in the U.S. felt the urge to step in during the COVID-19 Indian crisis [1]. This was made possible through telehealth services and remote consultations. Although telehealth is not a new technology, the spread of the pandemic urged the healthcare industry to work around the hurdles and expedite its adoption worldwide [2]. Telehealth has proven to be a practical, convenient, and beneficial tool in many healthcare services (e.g., during pregnancy and for aiding diabetic and psychiatric patients) [3]–[5]. Shifting from face-to-face to remote and virtual interactions can help to maintain ongoing care and treatment despite travel restrictions and geographic boundaries.

The unprecedented challenges posed by the pandemic have led to redesign the healthcare model to triage and timely deliver services while reducing the risk of contamination and transmission of COVID-19 [6]. Technology and expense are important factors that can play a major role in curbing and limiting the integration and interoperability of telehealth into the healthcare model [7]. Technological limitations include both hardware and software as well as internet access. Personnel healthcare devices must be leveraged to enable healthcare providers to provide telehealth services smoothly without depending on special technological features or devices [8]. The lack of staff trained to provide medical services remotely was another hurdle that COVID-19 proved can be overcome.
All medical correspondents should be trained on telemedicine platforms and devices to ensure that proper consultation is received adequately by the patient [6]. Privacy and medical confidentiality of the patients are also some of the challenges that exist in today’s telehealth systems. However, with the advancement in technology and cybersecurity, telehealth privacy and security can be sustained. Consequently, telehealth has proven to be a beneficial technology that has the potential to mitigate the spread of the infectious COVID-19 [9]. Doctors and medical practitioners can reach patients at the convenience of their own homes using telehealth. Furthermore, when resources are scarce and protective personnel equipment (PPEs) are limited in quantities, telehealth can greatly reduce the risk of contamination and the spread of infections [8]. Furthermore, it helps in providing ongoing care and treatment regardless of geographic location.

Blockchain is an immutable and tamper-proof ledger which keeps its records in a shared ledger. It is a peer-to-peer network that has immutable event logs which are an important tool for history tracking and tracing. During the pandemic, blockchain has proven to be an integral part in fighting against COVID-19 [10]. In this paper, we propose a blockchain-based telehealth system. It is a decentralized solution which aims to respect the confidentiality of the healthcare industry and the privacy of its users. To implement trust, accountability, and transparency, we use a private blockchain that respects the confidentiality of the patients and the medical practitioners. Our solution incorporates digital smart contracts that are programmable to register users and achieve three main goals of the telehealth industry such as teleconsultation, drug administration, and medical testing for remote patients. Our proposed solution is a generic telehealth system which can be used in different medical use case scenarios and applications with minimal efforts and modifications. In our solution, each actor is held accountable for its actions using his/her own on-chain digital signatures. Each executed function creates an event which is logged and timed for reference and history tracking.

A. RELATED WORKS AND CONTRIBUTIONS

Telehealth equipped with the intrinsic security features of the blockchain technology has been showing promising results during the pandemic as can be seen in [11]–[15]. Herein, we review the existing works focused on the integration of telehealth with blockchain technology.

The authors in [16] presented a telehealth architecture that incorporates blockchain technology. The solution involved multi-access edge computing (MEC), elliptic curve cryptography, Internet of things (IoT), and Fifth-generation (5G) communications technology. They mainly focused on the service architecture. Hence, there were no details mentioned on the smart contracts involved, code, testing, or implementation details. However, they have created a scenario to test their service architecture using Raspberry pi devices and the Hyperledger Fabric. They have shown great details on the IoT devices and the MEC nodes.

On the other hand, the authors in [17] highlighted the importance of using blockchain technology to track physicians’ burnout and stress level during the COVID-19 pandemic. The research work aims to spot the light on frontline workers and showcases how blockchain can be leveraged to track their health and mental status especially with the additional burden of scarce and limited resources. They showcase the importance of blockchain and telehealth in monitoring chronically ill patients and in maintaining compliance standards in administrative processes. However, this study lacks implementation details. Also, the study emphasizes the importance of a permissioned blockchain network to comply with the Health Insurance Portability and Accountability Act (HIPAA).

Since it is crucial to monitor the early signs and symptoms of COVID-19, the authors of [18] presented a mobile health care system that asynchronously provides patients with the needed medical attention. The patients use their mobile devices for ongoing real-time monitoring. Other patients can use their smartphones for an early diagnosis based on their communicated symptoms. The solution depends on smartphones and blockchain technology. However, there is no detailed implementation information on the use of programmable smart contracts or testing information.

To overcome the efficiency and technical issues faced during the pandemic with regards to convalescent plasma (CP) transfusion, the authors in [19] proposed a specialized framework. The study highlights the importance of telehealth and the needs of critical patients that require a speedy transfusion. Hospitals offering telehealth vary in terms of management policies. Hence, to overcome the interoperability issues and focus only on finding a donor and match pair, the authors present a framework that focuses mainly on telehealth for convalescent plasma (CP) transfusion across centralized and decentralized hospitals.

In summary, the aforementioned works agree on the importance of telehealth and its contributions. For example, the authors in [20]–[23] emphasized on the role of telehealth when there was an acute shortage in resources such as PPE, ventilators, medical supplies and devices. The pandemic helped to rapidly overcome hurdles such as expenses, reimbursement, policies and management, and paved the future of telehealth. However, the current literature lacks enough research on blockchain-based telehealth solutions and the opportunities that can be acquired when a complete solution is designed and implemented using programmable smart contracts. High-performance patient data management with preserved data security, privacy, accessibility, availability, and provenance health records are all features that can be achieved using the distributed blockchain ledger. The peer-to-peer network offers no manipulation on the patient and doctor data using its tamper-proof logs and restrictions on function executors [13]. Our solution leverages blockchain features to ensure transparency, privacy, and security.

The main contributions of this paper can be summarized as follows:
We propose a blockchain-based decentralized solution for telehealth services, which does not depend on third parties or centralized servers.

We show how to integrate our decentralized on-chain framework with off-chain storage systems such as cloud storage or a decentralized storage system as that of the Interplanetary File System (IPFS). Off-chain storage is used for storing and keeping track of large-size digital content such as video calls of telehealth sessions.

We develop four smart contracts along with six algorithms to register the participating entities and offer the patients different telehealth services in a manner that is transparent, traceable, auditable, private, secure, and trustworthy.

We implement and test the developed smart contracts for three different telehealth services: teleconsultation, drug administration, and medical testing. We make the code publicly available on GitHub.¹

Our proposed blockchain-based telehealth solution is generic enough to be adapted into different use case scenarios with minimal efforts and modifications.

The rest of the paper is organized as follows. Section II presents the design details of the proposed blockchain-based solution followed by the implementation details in section III including the smart contracts and algorithms. Section IV presents the testing details followed by section V which showcases the security analysis and comparison with the existing solutions along with discussing generalization aspects. Section VI concludes the paper.

II. SYSTEM DESIGN

This section describes the details of our system design. It explains the breakdown of our solution and presents the sequence of events in the smart contracts and solidity code. Figure 1 shows the components of the proposed blockchain-based solution. The system depends on the doctors and the medical practitioners who aim to provide in-home treatment services remotely. The doctors rely on teleconferencing calls to see and hear the patients and assess their needs. Medical drugs are administered as needed as well as medical tests are carried out when necessary. Courier services are also used to make treatment and testing possible. The video calls are all recorded and uploaded on a cloud storage or a decentralized storage platform such as IPFS. The system is managed, traced, and tracked through blockchain. The role of each part in the system is also explained below in further detail.

A. PARTICIPANTS

To facilitate the telehealth process on-chain, the participants need to communicate using smart contracts. As can be seen in figure 1, the participants are the patients at their own homes, medical facilities (hospitals, medical centers, etc.), courier services, drug stores, medical insurance companies, and the Ministry of Health.
homes. Also, the figure shows the medical doctors and nurses who connect remotely to the patient. Moreover, other than the medical facilities such as hospitals and medical centers, courier services play a vital role in the process to enhance the telehealth process and facilitate in-home testing and treatments for the patients. In addition, since the practicing practitioners will require medications when needed by the patients registered, affiliated drug stores are also important participants along with the medical insurance companies to cover the cost of the treatments for the insured patients. Also, the Ministry of Health is a higher authority that ensures all the medical practitioners and drugs are authorized and registered. This assures trust and governance.

B. FRONTEND LAYER AND APIs
The participant can communicate on the chain through Decentralized Applications (DApps) which use Application Programming Interfaces (APIs) to talk to the decentralized blockchain. There are several APIs that can be used to establish good communication between the participants and the blockchain. These APIs include Web3.js, Infura, RestHTTP, and JSON RPC as can be seen in figure 1. Those APIs help in providing requests and subscriptions based responses. Infura ensures that the participants have accessed information based on the latest network updates [24]. The latest network updates include events such as the courier or the nurse reaching the patient, alerts about the patient’s health and vitals, actions including the doctor uploading the recorded virtual call on the decentralized storage.

C. SMART CONTRACTS
We develop four smart contracts. The smart contracts are written in Solidity using the Remix IDE [25]. The first smart contract (SC) is the Registration SC. The Registration SC is required to ensure that only the authorized participants can communicate on-chain and execute function calls. It has functions that register doctors, nurses, and couriers. It can also disallow a previously registered participant from gaining access privileges and executing function calls. This is done through mappings, boolean variables, and the Ethereum Addresses (EAs) of the participants. Each other smart contract from the remaining three inherits the variables and functions of the Registration SC. This is because before executing any call, the SC would check if the caller’s EA is registered and authorized. The registration SC can also be used to help in assessing the qualifications of the actors such as the doctors, nurses, and couriers. Their EAs can be linked to an off-chain reputation system as well as IPFS. The IPFS public file associated with each EA contains details of the actors’ background, education, experience, and career. The IPFS hash of the file can only be stored on-chain during registration. This is important to avoid storing large content on-chain and compromising execution costs. The other smart contracts are used for telehealth calls (i.e., Teleconsultation SC, Medical Testing SC, and the Drug Administration SC). Their functions as well as events and flow sequence are all detailed in the following section.

D. BLOCKCHAIN
A private blockchain is the core of this distributed and decentralized design. The digital ledger securely keeps a record of all the transactions and maintains a chronological history keeping reference [26]. A programmable blockchain uses smart contracts to execute logic through function calls and emitted events [27]. To protect the privacy of the patients and medical confidentiality, a private Ethereum blockchain...
and simplicity, smart contracts were used in the design and implementation. However, the design is not limited to private Ethereum blockchains such as Quorum [28], Hyperledger Besu [29] but can also be implemented on any other private blockchain including Hyperledger Fabric [30]. Ethereum private blockchains use smart contracts and can use solidity for writing smart contracts. However, they may vary with the applied consensus algorithm. For instance, Besu supports Proof-of-Authority (PoA) and Istanbul BFT (IBFT); whereas, Quorum supports Raft and Istanbul BFT [28], [31]. Besu also offers identity management through a separate component known as 'EthSigner'; whereas, Quorum does not support identity management [28], [32]. On the other hand, Fabric uses chain-codes and has very flexible plug-and-play consensus, components, and membership services [30]. Based on the requirements, needs, and implementation costs, a private blockchain can be chosen.

E. OFF-CHAIN STORAGE: CLOUD AND IPFS

Off-chain storage is used to store the recorded audio/video calls. The doctor records the virtual video calls where teleconsultation, medical testing, and drug administration take place. The video is then uploaded by the doctor to the cloud or a decentralized storage system such as IPFS. Cloud can be used if all parties trust the cloud provider. Otherwise, a fully decentralized storage system can be used with an added level of security using proxy re-encryption. This would allow multiple parties, such as care givers and patients to access the uploaded encrypted files securely. The hash of the recording is only used on-chain for history tracking, tracing and as a reference for the participants when needed. Another use of off-chain storage is when the courier picks up the medical kit from the patient to deliver it to the doctor. The medical kit received from the patient is first captured by the courier, uploaded on the cloud or the IPFS, then its hash is used on-chain.

F. TELECONSULTATION SC

The Teleconsultation SC is designed to accommodate all requests by patients at the convenience of their homes. The registered patient, nurse, and doctor communicate on-chain and provide the patient with the consultation needed. Figure 2 shows the sequence of the function calls and the emitted events that take place in the smart contract. The sequence diagram illustrates how the nurse first confirms the appointment with the patient on-chain and waits for a response from the patient. Then the doctor starts the video call which is recorded and uploaded on the decentralized storage of the IPFS. The consultation is done through a video call between the doctor and the patient. When the call ends, the doctor then uploads the recording of the video call to the IPFS and stores the hash on-chain. The hash is kept on-chain as a reference for all the participating entities and history tracking and tracing purposes.

G. DRUG ADMINISTRATION SC

A patient at home may require the administration of drugs under the doctor’s supervision and accompanied by a nurse. Therefore, this telehealth service facilitates for the patient to have a nurse arrive at their home to administer the drugs. The remotely located practitioner must approve that the patient is qualified to take the medication. The nurse first confirms the appointment with the patient. Then the patient would wait for the nurse’s arrival at the patient’s home. Figure 3 shows the sequence of events in a Drug Administration SC. The nurse announces her arrival on the chain. Then the patient also agrees that the medical assistance (nurse) reached them. The doctor then starts the video call and documents the time on-chain. The nurse measures the patient’s vitals which include their blood pressure, temperature, oxygen saturation, and heart rate. The vitals are examined by the doctor and the doctor would then either approve administering the drugs to the patient or refuse it. The green section in figure 3 shows the sequence of events after the doctor grants the permission to administer the drugs. The nurse confirms administering the drugs to the patient which allows the doctor to end the video call. The recorded video call is then uploaded by the doctor on IPFS. The hash of the call is used on-chain to enhance tracking, tracing, and history recording. The sequence of calls and events can also be customized depending on the case and the disease cured. Furthermore, this telehealth case is not restricted to Covid-19 or infectious diseases as it can be used to administer drugs for other diseases as required by the physician.

Another possible option that the patients can opt for is having the drugs administered by themselves. To make that possible, a trusted registered courier has to transfer the medical kit to the patient for drug administration. The process at the beginning follows the same procedure as previously mentioned where the appointment is confirmed by both the nurse and the patient. Then instead of the nurse arriving at the patient’s home, a medical kit arrives with a registered courier. Figure 4 shows the details and sequence of events as the courier arrives at the destination and the patient confirms on the chain the arrival of the medical kit with the courier. The role of the nurse here is just to confirm the patient’s appointment. The doctor initiates the video call then requests the patient to measure the vitals. Based on the vitals measurements, the doctor advises the patient to take the drugs or not. If the patient is medically fit, the doctor requests the patient to take the drugs. Then the call is ended by the registered doctor. The recording of the call is also uploaded on IPFS and its hash is added on-chain.

H. MEDICAL TESTING SC

A doctor might require a patient at home to perform a medical test to better study the perceived symptoms or to check on the body’s improvement status with the prescribed medications. In all cases, the doctor needs the medical test to be performed correctly and accurately just the way it would be in the
medical center or hospital. Therefore, the nurse first requests for an appointment confirmation from the patient. Then, after the appointment is confirmed as can be seen in Figure 3, the patient waits for the arrival of the registered nurse. When the patient confirms that the nurse has arrived, the doctor initiates the video call. The vitals are measured by the nurse to ensure that the patient is medically fit to take the test. These steps are similar to the steps taken before the drug is administered. Hence, they are common for both the medical testing SC and the drug administration SC as seen in Figure 3. Based on the vitals readings measured by the attending nurse, the doctor decides if the patient can have the medical test done. If the patient is allowed by the doctor, the doctor on-chain executes a function called \texttt{StartTest(bool)} which shows that the doctor authorized the patient to take the test. The nurse then performs the test and announces it on-chain. At the end, the recorded video call is uploaded on a decentralized storage such as IPFS and the hash is used on-chain for history recording, tracking, and tracing. The sequence of function calls and events are highlighted in Figure 3.

The medical testing can also be performed by the patient without the nurse and under the supervision of the doctor. To do so, the registered courier delivers a medical kit to the patient. The medical kit will have the needed medical equipment for the patient to perform the test. The procedure is followed like before except that now the patient waits for the
Fig. 4. Drug administration and Medical Testing SCs sequence diagram with a registered courier.

arrival of the medical kit by the courier after the appointment is confirmed. Figure 4 shows how the courier announces the arrival at the destination followed by a confirmation by the patient. The doctor then initiates the call. The doctor also requests the patient to measure the vitals. If the patient is medically fit, the doctor authorizes the patient to perform the medical test under the doctor’s supervision. The test is performed while the doctor is talking and viewing exactly how the patient is following the doctor’s instructions. When the test is done, the medical kit is returned by the patient to the courier and the courier takes it back to the doctor. The courier takes a photo of the medical kit package, uploads it to the IPFS storage, and then includes the IPFS hash of the uploaded image on the chain. The uploaded hash of the image ensures that the courier has taken the package from the patient and is also used for reference and history tracking purposes. The doctor then ends the call and adds the hash of the recorded video call on the chain as well.

III. IMPLEMENTATION DETAILS

In this section, we present the implementation details of the three main smart contracts; namely, Teleconsultation Smart Contract (SC), Drug Administration SC, and Medical Testing SC. The code of all the telehealth SCs along with Registration SC is written in Solidity using the Remix IDE [25]. It is compiled and tested using Remix. Below are given the details of the functions, algorithms, and sequence of events that occur in the SCs. Each algorithm is accompanied by an explanation that describes how this algorithm is applied in each SC and the key differences if any exist. The algorithms are ordered based on the events. Hence, they start with the appointment confirmation and end with the virtual call terminated by the doctor. In our proof of concept implementation, we decide on going with a fully decentralized storage option. Hence, we use the IPFS hash in our code and algorithms. However, if the leading participating entities decide on cloud storage, the hash of the file stored on the cloud can be used in the place of the IPFS hash in our implementation.

A. NURSE APPOINTMENT CONFIRMATION REQUEST

The three main smart contracts implemented for telehealth service start with the nurse requesting an appointment confirmation from the patient. Algorithm 1 shows the details of the AppointmentConfirm function. This function can only be
executed by the registered nurse. It takes the time and the patient Ethereum Address (EA) as parameters. Furthermore, in the Drug Administration SC and the Medical Testing SC, the function also takes the appointment type. This additional parameter helps identify if the medical assistance home service would include a nurse or only a courier. In this algorithm, the state of the contract is checked at first to ensure it is the first state as expected which is `waitingforanewappointment`. Additionally, the EA of the patient passed as a parameter is checked to ensure it is a registered patient. This function updates the contract state and emits an event to alert the patient to confirm the appointment on-chain.

**Algorithm 1: Nurse Appointment Confirmation Request**

| Input | \(patient\), \(caller\), \(nurse\), \(time\), \(state\) |
|-------|---------------------------------|
| 1 \(patient\) | holds the Ethereum Address of the patient. |
| 2 \(caller\) | holds the Ethereum Address of the function caller. |
| 3 \(nurse\) | holds the Ethereum Address of the registered nurse. |
| 4 \(state\) | is a variable that has the contract state. |
| 5 \(RegisteredPatientList\) | is a list that has all the registered patients. |
| 6 if \(caller == nurse \land state == waitingforNewApp \land patient \in RegisteredPatientList\) then |
| 7 \(currentPatient = patient\) |
| 8 Emit a Request Appointment Confirmation alert using the patient EA and time. |
| 9 \(state = appConfirmedbyNurse\) |
| 10 end |
| 11 else |
| 12 Show an error and return the contract to the previous state. |
| 13 end |

B. APPOINTMENT CONFIRMATION BY THE PATIENT

Once a nurse requests an appointment confirmation by the patient, the patient executes the function `ConfirmAppointment` that follows the logic of algorithm 2. The Teleconsultation SC does not require the appointment type parameter and uses only the time as an input. However, since the other smart contracts offer different services that involve a delivery with the courier or a nurse home service, an appointment type is a second parameter that algorithm 2 would accept in the Administering Drugs SC and the Medical Testing SC. In this algorithm, the state is updated to `appConfirmedbyPatient` and an event is emitted announcing the patient’s appointment confirmation. In order for this function to execute, the caller must be the current registered patient and the smart contract state should be `appConfirmedbyNurse`.

C. MEDICAL KIT OR NURSE ARRIVAL AT THE DESTINATION

The Medical Testing SC and the Drug Administration SC require the arrival of the nurse to the patient’s home or the arrival of the courier with a medical kit. Hence, algorithm 3 in function `ArrivedAtDestination` is used to confirm the arrival of the medical assistance to the patient’s home. This algorithm is not needed in the Teleconsultation SC as no medical nurse or courier is required to be available at the patient’s home. Therefore, this function checks if the caller is a registered nurse or if it’s the registered courier. Furthermore, the appointment type is checked also along with the caller’s Ethereum address to ensure that the patient appointment type matches the home service they are receiving. An appointment type of ’1’ means that the nurse arrived and an appointment type of ’2’ means the patient is only expecting a medical kit with a courier. This algorithm is executed after algorithm 3 is completed and the appointment is confirmed by the patient. At the end of this algorithm, based on the appointment type, the state is updated to either `NurseArrived` or `KitArrived` respectively. Additionally, an event is emitted to announce that the medical assistance reached the registered patient.

The execution of this function notifies the patient that he/she needs to confirm the arrival of the medical assistance to the home before the doctor can initiate a video call. Therefore, the function `ConfirmArrival` or `ConfirmMedicalKitArrival` can only be executed by the registered patient after algorithm 6 is completed. The state would then be updated to `NurseArrivalConfirmation` or `KitArrivalConfirmation` respectively. Also, an event is emitted that announces the medical assistance arrival is confirmed by the patient.

D. CALL INITIATION BY THE DOCTOR

Once the appointment is confirmed and all the needed medical assistance is available for the patient, the call is initiated by the doctor. This video call is essential in all types of telemedicine services offered. Therefore, all the three smart contracts have the `CallInitiated` function which can only be executed by the registered doctor. In this function the state is checked to ensure that the patient is ready and have
Algorithm 3: Medical Kit or Nurse Arrival at the Destination

Input : caller, time, nurse, state, courier, appType
1 nurse holds the Ethereum Address of the registered nurse
2 courier holds the Ethereum Address of the registered courier
3 currentPatient holds the Ethereum Address of the registered patient
4 caller holds the Ethereum Address of the function caller
5 state is a variable that has the contract state
6 appType is a variable that has the appointment type
7 if caller == nurse ∨ caller == courier) ∧ state == appConfirmedbyPatient
8 Emit an event stating that the medical assistance reached patient currentPatient
9 if appType == 1 then
10 state = NurseArrived
11 end
12 else
13 state = KitArrived
14 end
15 end
16 else
17 Preview an error and return the contract to the previous state.
18 end

Algorithm 4: Call Initiation by the Doctor

Input : caller, time, doctor, state
1 doctor holds the Ethereum Address of the registered doctor
2 caller holds the Ethereum Address of the function caller
3 state is a variable that has the contract state
4 if caller == doctor ∧ state == appConfirmedbyPatient
5 Emit an event showing the video call request is sent by the doctor
6 state = CallInitiatedbyDoctor
7 end
8 else
9 Preview an error and return the contract to the previous state.
10 end

Algorithm 5: Vitals Measurement

Input : caller, time, patient, state, BpHR, TOx
1 currentPatient holds the Ethereum Address of the registered patient
2 caller holds the Ethereum Address of the function caller
3 state is a variable that has the contract state
4 BpHR is a variable that holds the blood pressure and the heart rate.
5 TOx is a variable that stores the temperature and the oxygen saturation.
6 if (caller == nurse ∧ state == CallJoinedbyPatient) \lor (caller == currentPatient ∧ state == VitalsMeasurementRequest)
7 Emit an event stating that the vitals have been sent and the call is in progress
8 state = VitalsMeasured
9 end
10 else
11 Preview an error and return the contract to the previous state.
12 end

Algorithm 6: Video Call Request

Input : caller, time, doctor, state
1 doctor holds the Ethereum Address of the registered doctor
2 caller holds the Ethereum Address of the function caller
3 state is a variable that has the contract state
4 if caller == doctor ∧ state == appConfirmedbyPatient
5 Emit an event stating that the medical assistance reached patient currentPatient
6 if appType == 1 then
7 state = NurseArrived
8 end
9 else
10 state = KitArrived
11 end
12 end
13 else
14 Preview an error and return the contract to the previous state.
15 end

E. VITALS MEASUREMENT

After the video call is joined by the patient, depending on the purpose of the call, the patient’s vitals might be needed. The Drug Administration SC and the Medical Testing SC require that the patient’s vitals are measured and sent on-chain to proceed. If a nurse is available with the patient at home, then the nurse automatically executes algorithm 5 and sends the vitals. However, if the patient is alone at home without a nurse and received the medication or medical kit with the courier, the patient would be guided by the doctor and told on-chain to measure the vitals. The patient would then execute algorithm 5 and send their vitals. The vitals measured include blood pressure, heart rate, temperature, and oxygen saturation. Hence, algorithm 5 shows how the vitals are sent on-chain by either the nurse or the patient. Furthermore, the state is updated to VitalsMeasured and an event is emitted to notify all the listening parties about the new update. Following the vitals measurement, the doctor would then authorize proceeding with the medical test or drug administration if the patient is fit. If the vitals are not within the normal range, the doctor will not authorize the patient to proceed and the call would end as would be explained in algorithm 8.

F. Covid19 DRUGS ADMINISTRATION

For the drugs to be administered or the medical test to be done, the patient must be fit and their vitals should be normal. Therefore, algorithm 6 allows only the doctor to
Algorithm 6: Administer Covid19 Drugs

Input : caller, result, doctor, state
1 doctor holds the Ethereum Address of the registered doctor
2 result holds a boolean
3 caller holds the Ethereum Address of the function caller
4 state is a variable that has the contract state
5 if caller == doctor ∧ state == VitalsMeasured then
6     if result == true then
7         Emit an event stating that the patient is authorized to take the drugs
8         state = AuthorizedToTakeMeds
9     end
10 else
11     Emit an event showing that the authorization is not given
12     state = NotAuthorizedToTakeMeds
13 end
14 end
15 else
16     Preview an error and return the contract to the previous state.
17 end

make this call and to provide an authorization on-chain for the patient to receive the drugs in the Drug Administration SC. The same logic is also applied in the Medical Testing SC. This would change the state to AuthorizedToTakeMeds accordingly. If the patient is not authorized, then the state is updated to NotAuthorizedToTakeMeds. In both cases mentioned, events are emitted to update the listening parties about the authorization. If the patient is authorized to take the medication or take the medical test, the function Covid19MedicationAdministered or TestCompleted is executed by the patient or the nurse depending on whether the patient requested a nurse along or only a courier service. This would update the state to MedsAdministered or TestCompleted accordingly.

Algorithm 7: Medical Kit Pickup

Input : caller, time, courier, state, photoHash, currentPatient
1 courier holds the Ethereum Address of the registered courier
2 caller holds the Ethereum Address of the function caller
3 state is a variable that has the contract state
4 photoHash is a variable that holds the hash of the uploaded package photo by the courier
5 currentPatient holds the Ethereum Address of the registered patient
6 if caller == courier ∧ state == TestCompleted then
7     Emit an event stating that the medical kit is on the way using the photoHash, time, currentPatient
8     state = MedicalKitOnTheWayToDoctor
9 end
10 else
11     Preview an error and return the contract to the previous state.
12 end

Algorithm 8: Call Ended by the Doctor

Input : caller, time, doctor, state, vidHash
1 doctor holds the Ethereum Address of the registered doctor
2 caller holds the Ethereum Address of the function caller
3 state is a variable that has the contract state
4 vidHash is a variable that holds the IPFS hash of the uploaded video call
5 if caller == doctor ∧ state == CallJoinedbyPatient then
6     Emit an event stating that the video call has ended and provide the vidHash
7     state = waitingForNewApp
8 end
9 else
10     Preview an error and return the contract to the previous state.
11 end

G. MEDICAL KIT PICKUP

The function PickMedicalKit is only available in the Medical Testing SC and it follows the logic described in algorithm 7. This algorithm can only be executed by the registered courier, only when the medical test has been completed. Therefore, the EA of the caller is checked to match the EA of the courier, and the state is checked to ensure that the test has finished. The courier would take photos of the medical test packaged for delivery and would hash the photos that are uploaded on the IPFS servers. The hash of those photos is passed as an attribute in the function call along with the patient’s EA and the time. An event is then emitted to update everyone on-chain that the medical kit is on its way to the doctor and the state is also updated.

H. CALL TERMINATION BY THE DOCTOR

In our smart contracts; namely, Teleconsultation, Medical Testing, and Drug Administration SCs, the video call is ended by the doctor after the purpose is achieved. Algorithm 8 shows the details of the call termination by the registered doctor. The function takes the EA of the doctor, the state, and a hash. This hash is the hash of the video call that is uploaded by the doctor to the decentralized IPFS servers. The doctor first uploads a video of the recorded virtual call, then executes the algorithm and uses the hash of the uploaded video as an attribute. In this algorithm, the caller’s EA is first checked to ensure that only the doctor can execute this function. Also, the state must be checked and this varies
depending on the type of smart contract. In the Teleconsultation, Medical Testing, and Drug Administration SCs, the smart contract state must be either CallJoinedbyPatient or MedicalKitOnTheWayToDoctor or MedsAdministered accordingly. Furthermore, if the patient was not allowed to take the test or the drugs, then the call would end and hence the state can also be NotAuthorizedToTakeTest or NotAuthorizedToTakeMeds, respectively. After verifying the state, an event is emitted to announce that the video call with the hash ’vidHash’ has ended. Finally, the state of all contracts would be updated to waitingForNewApp which states that the contract is ready to accept new appointments.

IV. TESTING AND VALIDATION
Our blockchain-based telehealth solution consists of four smart contracts such as Registration, Teleconsultation, Drug Administration, and Medical Testing Sc. These smart contracts were tested for correct execution, expected results, and the right restrictions. The testing is done using the Remix [25] IDE. The functions can only be executed in a particular order. This is done based on the smart contract state. Each function checks for the contract state before its execution and updates it to the next one as needed. Only registered users can execute the functions based on their roles. Before testing any of the medical smart contracts, the users are first registered in the Registration SC. The following subsections show results from the testing of the smart contracts. In our testing scenarios, the doctor holds 0x480897b0513d7C7541B6d9D7E929C4e5364D2dB0 as Ethereum address (EA), the nurse holds 0x14723A09ACff6D2A60DcdF7aA4AFf308FDDC160C as EA, the patient holds 0xA6B483F64d9C6d1EcF9b849ae677dD3315835cb24 as EA and the courier holds 0x583031D1113aad414F02576BD6afaBfb302140225 as EA.

A. NURSE APPOINTMENT CONFIRMATION
For any of the telehealth services such as teleconsultation, Drug Administration or Medical Testing, a patient must first confirm their requested appointment. Hence, in the function AppointmentConfirm, the nurse requests the registered patient to confirm their availability at the requested appointment. Figure 5 shows the registered nurse executing the function and successfully emitting an event RequestAppointmentConfirmation with the appointment time.

B. APPOINTMENT CONFIRMATION BY THE PATIENT
The patient can then respond to the nurse’s request and confirm the appointment through the function ConfirmAppointment. Figure 6 shows the logs and the event that announces the patient successfully confirming the appointment as requested by the nurse. This functionality has been tested in all the three smart contracts of the telemedicine functions as it is a common function needed by all three health services.

C. MEDICAL ASSISTANCE ARRIVAL
Both the Drug Administration and Medical Testing SCs require either the nurse or the courier to arrive at the patient’s home. Hence, this function in both smart contracts is tested successfully. The function ArrivedAtDestination was successfully executed in the Medical Testing SC as can be seen in figure 7. The event MedicalAssistanceReachedPatient is emitted and the patient appointment is of type ‘2’ in the decoded input, which indicates that the courier has arrived at the patient’s home and not the nurse.

D. CALL INITIATION BY THE DOCTOR
When the patient is ready with all the needed medical assistance, the doctor initiates the call through the function.
CallInitiated. The function is available in all the three telemedicine smart contracts. This function is successfully tested as can be seen in figure 8 where the event CallStarted is emitted to notify the listeners and the patient that the virtual call has commenced.

**E. VITALS MEASUREMENT**
The VitalsMeasured function can be executed by the nurse or the patient depending on the appointment type. This function helps the doctor better assess if the patient can be administered the drugs or take the medical test. The function is successfully tested where the patient vitals are available in the decoded input in figure 9 and the event VitalsSent and CallInProgress is emitted to let the doctor and all participating entities be aware of the patient vitals.

**F. DRUGS ADMINISTRATION**
In the Drug Administration SC, the drugs are administered based on the vitals results and the authorization from the doctor. The function AdministerCovid19Meds is executed by the doctor only and an event ProceedWithMeds is emitted based on the doctor’s authorization decision as shown in figure 10. In our testing, the event was emitted successfully which indicates that the patient is ready to receive the drugs.

**G. MEDICAL KIT PICKUP**
The medical kit is picked up from the patient by the courier once the medical test has ended. The Medical Testing SC allows the courier to execute the PickMedicalKit function to indicate that the kit is picked up from the patient. The function takes the photo hash of the medical kit as well as the decoded input included the photo hash as $bytes32$, $0 \times 3fd54831f488a22b28398de0c567a3b064b937f54f81739ae9bd54b9ae9bd545967f3abab$. Also, the event MedicalKitOnTheWayToDoctor is emitted successfully.

**H. CALL TERMINATION BY THE DOCTOR**
At the end of the telehealth call, the video call is terminated by the doctor. The doctor uploads the video on IPFS and the hash is then used on-chain for tracing and tracking. The video call hash $0xe0f89ca8eae95281590977802df657506a151304234d15570c12cc26263a8b7a$ is part of the decoded input as seen in figure 12. The event Covid19TestCompleted is emitted successfully in the logs which indicates the end of the medical test in the Medical Testing SC.

**V. DISCUSSION**
In this section, we evaluate our solution using different security parameters. We also showcase how our solution is generic and can be adapted as per the need of emerging medical applications.
Table 1. Comparison with other telehealth frameworks.

| Solution | Features | Storage | Description | Blockchain Role | Smart Contracts | Blockchain Type |
|----------|----------|---------|-------------|-----------------|----------------|-----------------|
| [16]     | Uses multi-access edge computing (MEC), elliptic curve cryptography, internet of things (IoT) and 5G. | Uses IPS and blockchain | Connecting multiple medical devices and ensuring access control to patients information | Hyperledger Fabric used for registration and monitoring MEC nodes | Uses smart contracts but their implementation is not mentioned | Permissioned |
| [17]     | A proposal to use blockchain and smart contracts to monitor the health of physicians | Blockchain | Track the physicians burnout and stressors during the COVID-19 pandemic | Trace and notification | Only a proposal, no implementation | Permissioned |
| [18]     | Use IoT, smart phones and blockchain to monitor Covid-19 patients | Cloud and blockchain | Asynchronous telehealth system for monitoring early COVID-19 symptoms | Monitoring | - | - |
| [19]     | Finding a way to match donors with patients across telehealth hospitals | Blockchain, servers | Telehealth for convalescent plasma (CP) transfusion across centralized and decentralized hospitals | Updated ledger of patient details | - | - |
| **Our Proposed Solution** | Providing three types of telehealth services: 1) Teleconsultation 2) Drug Administration 3) Medical Testing | IPS, Cloud, Blockchain | A fully decentralized telehealth system using permissioned Ethereum network | Tracing, tracking, alerting with notifications, and provenance | Yes, made publicly available | Permissioned Ethereum |

Figure 12. Logs showing the virtual telehealth call has ended along with the uploaded call hash.

### A. SECURITY ANALYSIS

Blockchain is a disruptive technology that provides intrinsic security features. It is the highlight of our solution where its characteristics are utilized to best fit the needs of our framework. It eradicates vulnerabilities and exploits that threaten trust, integrity, accountability, authorization, confidentiality, non-repudiation, and transparency. Its immutable records are tamper-proof and its logs provide provenance and help in tracing and tracking.

Integrity is a security feature that enforces trust. In our solution, the participating entities whether the medical practitioners or the patient or delivery couriers should be trusted. Hence, trust is enforced through the tamper-proof logs. The actions taken by the participating entities on-chain such as confirming appointments or administering drugs are all tamper-proof. Hence, on-chain decisions cannot be exploited.

Accountability is a vital characteristic that could clear disputes and ensure that participating entities are held responsible for their actions. Each action on-chain is signed digitally using the Ethereum Address (EA) of the caller. This imposes non-repudiation. Each participating entity has a unique EA and all transactions are signed by the caller’s address.

Moreover, authorization is mandatory in our solution as the system is to be used in the medical field where the patient’s information must be treated with confidentiality. Only the authorized parties can execute the function calls. This is ensured in our solution by associating every EA with an identity during registration in the registration SC. Hence, in the execution, only a doctor, for instance, can authorize a medical test for a registered patient. Also, only a courier can upload the hash of the delivered package on-chain.

Furthermore, confidentiality is crucial in ensuring the solution protects the patient’s privacy and medical rights. Therefore, our solution is implemented using a private blockchain. Based on the EA of the user, their rights are provided as well as authority levels and access rights. Furthermore, during registration off the chain, the biometrics data of the individuals are associated with their EAs or on-chain addresses on the chain [33]. Moreover, depending on the chosen private network, the information is encrypted when communicated. Other networks depend on channels and divide the participating entities into groups [34]. Roles and access rights can be administered by a higher authority such as Membership Service Providers (MSP). Hyperledger Fabric uses channels for confidentiality and the MSP for identity management [35].

### B. COMPARISON WITH EXISTING SOLUTIONS

Table 1 compares the existing blockchain-based telehealth solutions with our solution. The solution proposed in [16] was implemented using a permissioned blockchain network. The solution depends on IoT devices and focuses on secure communication between the multi-access edge computing nodes.
and the IoT devices. Furthermore, the solution uses smart contracts and implies that the testing was done using a raspberry pie and the Hyperledger Fabric. One of the limitations of that work is it does not show the testing and coding details of the smart contracts. Unlike the other solutions proposed in [17]–[19], our proposed solution deals with three main telehealth services for patients which are teleconsultation, drug administration, and medical testing. Also, it is fully decentralized using the decentralized storage of IPFS or can be integrated with the cloud. Moreover, our study shows the full implementation and testing details along with the smart contracts’ code which is made publicly available on GitHub.

C. GENERALIZATION

Our proposed blockchain-based telehealth solution helps to ease the burden of the medical professionals besides facilitating patients. It is fully applicable to the COVID-19 pandemic and other infectious diseases. The proposed solution is versatile and can be fully adapted for other purposes, diseases, and benefits. Our smart contracts’ functions can be edited and new functions can be added as required. Furthermore, new roles can also be applied as well as modifiers. This solution is designed to eradicate the spread of disease and to spread the knowledge of the medical practitioners as well as care and treatment. Patients seeking treatment and ongoing care can be handled regardless of their physical geographical location. Consequently, our solution is not restricted to infectious viruses, but it can be used for several other telehealth scenarios (e.g., diabetes, mental health, maternity checkups, etc.).

VI. CONCLUSION

In this paper, we have presented a private blockchain-based telehealth solution. The proposed solution ensures traceability, integrity, and availability of the telehealth transactions and records related to medical care, diagnostics, and monitoring for remote and at-home patients. Our proposed solution leveraged private blockchain intrinsic features to ensure trust, accountability, integrity, transparency, and privacy. This research contributes in paving the way towards facilitating better medical care for people in rural and inaccessible areas. It also expedites medical attention to remotely ill patients. Using the permissioned blockchain network, we were able to maintain the patient’s privacy and medical information securely. We showed how our system can be integrated with cloud and IPFS storage systems to facilitate the secure accessibility and traceability of immutuable large-size digital content and video calls associated with telehealth service sessions. Our proposed system along with its implementation details, as well as smart contracts and their algorithms are given and studied in this paper specifically for COVID-19 patients; however, all can be tailored and extended in general for remote patients. In the future, we plan to deploy the full system in a real Ethereum blockchain main network (Mainnet) and build the relevant end-user Decentralized Applications (DApps).

REFERENCES

[1] Indian American Doctors Pitch in With Free Telehealth Advice During India’s COVID-19 Crisis. Accessed: May 15, 2021. [Online]. Available: https://edition.cnn.com/2021/05/09/us/india-covid-doctors-us-telehealth-%help/index.html
[2] J. R. Maese, D. Seminara, Z. Shah, and A. Szerszen, “Perspective: What a difference a disaster makes: The telehealth revolution in the age of COVID-19 pandemic,” J. Med. Qual., vol. 35, no. 5, pp. 429–431, Sep. 2020.
[3] R. M. Reynolds, “Telehealth in pregnancy,” Lancet Diabetes Endocrinol., vol. 8, no. 6, pp. 459–461, Jun. 2020.
[4] T. Kompala and A. B. Neinstein, “Telehealth in type 1 diabetes,” Current Opinion Endocrinol., Diabetes Obesity, vol. 28, no. 1, pp. 21–29, 2021.
[5] K. A. Zoder-Martell, A. M. Markelz, M. T. Floress, H. A. Skriba, and L. E. N. Sayyah, “Technology to facilitate telehealth in applied behavior analysis,” Behav. Anal. Pract., vol. 13, no. 3, pp. 596–603, Sep. 2020.
[6] C. Shuchar, J. Engel, and G. Elwyn, “Implications for telehealth in a postpandemic future: Regulatory and privacy issues,” Jama, vol. 323, no. 23, pp. 2375–2376, 2020.
[7] E. E. Thomas, H. M. Haydon, A. Mehrotra, L. J. Caffery, A. L. E. N. Sayyah, and A. C. Smith, “Building on the momentum: Sustaining telehealth beyond COVID-19,” J Telemedicine Telecare, Sep. 2020. Art. no. 135763X20960638.
[8] L. H. Schwamm, A. Erskine, and A. Licurse, “A digital embrace to blunt the curve of COVID19 pandemic,” npj Digit. Med., vol. 3, no. 1, pp. 1–3, Dec. 2020.
[9] E. Monaghesh and A. Hajizadeh, “The role of telehealth during COVID-19 outbreak: A systematic review based on current evidence,” BMC Public Health, vol. 20, no. 1, pp. 1–9, Dec. 2020.
[10] R. W. Ahmad, K. Salah, R. Jayaraman, I. Yaqoob, S. Ellahham, and M. Omar, “Blockchain and COVID-19 pandemic: Applications and challenges,” Tech. Rep., 2020.
[11] S. Zawada, “Poster: Blockchain application feasibility in telehealth for DSCSA compliance,” in Proc. IEEE/ACM Int. Conf. Connected Health, Appl., Syst. Eng. Technol. (CHASE), Dec. 2020, pp. 3–4.
[12] V. Chamola, V. Hassija, V. Gupta, and M. Guzani, “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. 90225–90265, 2020.
[13] R. W. Ahmad, K. Salah, R. Jayaraman, I. Yaqoob, S. Ellahham, and M. Omar, “The role of blockchain technology in telehealth and telemedicine,” Int. J. Med. Informat., vol. 148, Apr. 2021, Art. no. 104399.
[14] D. Vervoort, C. R. Guetter, and A. W. Peters, “Blockchain, health disparities and global health,” BMJ Innov., vol. 7, no. 2, pp. 506–514, Apr. 2021.
[15] M. Mk, G. Srivastava, S. R. K. Somayaji, T. R. Gadekallu, P. K. R. Maddikunta, and S. Bhattacharya, “An incentive based approach for COVID-19 using blockchain technology,” 2020, arXiv:2011.01468.
[16] T. Dwivedi, A. Braekken, M. Ylianttila, and M. Liyanage, “Multi-access edge computing and blockchain-based secure telehealth system connected with 5G and IoT,” in Proc. GLOBECOM IEEE Global Commun. Conf., Dec. 2020, pp. 1–6.
[17] V. Dhillon, T. Xu, and C. Parikh, “Blockchain enabled tracking of physician burnout and stressors during the COVID-19 pandemic,” Frontiers Blockchain, vol. 3, p. 62, Feb. 2021.
[18] T. Alam, (Jan. 25, 2021). Blockchain-Enabled Mobile Healthcare System Architecture for the Real-Time Monitoring of the COVID-19 Patients. [Online]. Available: https://issn.com/abstract=3772643
[19] T. J. Mohammed, A. Albahri, A. Zaidan, O. Albahri, J. R. Al-Obaidi, B. Zaidan, M. Larbani, R. Mohammed, and S. M. Hadi, “Convalescent-plasma-transfusion intelligent framework for rescuing COVID-19 patients across centralised/decentralised telemedicine hospitals based on AHP group topsich and matching component,” Appl. Intell., vol. 51, no. 5, pp. 2956–2987, 2021.
[20] S. Bhaskar, A. Nurtuzina, S. Mittoo, M. Banach, and R. Weissert, “Telemedicine during and beyond COVID-19,” Frontiers Public Health, vol. 9, p. 233, Mar. 2021.
[21] S. Bhaskar, S. Bradley, V. K. Chattu, A. Adisesh, A. Nurtuzina, S. Kuyakhayeva, S. Sakhamuri, S. Moguilner, S. Pandya, S. Schroeder, M. Banach, and D. Ray, “Telemedicine as the new outpatient clinic gone digital. Position paper from the pandemic health system RESilience PROgram (REPROGRAM) international consortium (Part 2),” Frontiers Public Health, vol. 8, p. 410, Sep. 2020.
[22] H.-N. Dai, M. Imran, and N. Haider, “Blockchain-enabled Internet of Medical Things to combat COVID-19,” IEEE Internet Things Mag., vol. 3, no. 3, pp. 52–57, Sep. 2020.
HAYA R. HASAN received the B.S. degree in computer engineering from the American University of Sharjah, United Arab Emirates, in 2014, and the master’s degree in electrical and computer engineering from Khalifa University, United Arab Emirates, in 2018. She is currently a Research Associate with the Department of Industrial and Systems Engineering, Khalifa University. She is passionate about research especially in the field of blockchain and smart contracts. She has publications in her area of interests, blockchain and security.

KHALED SALAH (Senior Member, IEEE) received the B.S. degree in computer engineering with a minor in computer science from Iowa State University, USA, in 1990, and the M.S. degree in computer systems engineering and the Ph.D. degree in computer science from the Illinois Institute of Technology, USA, in 1994 and 2000, respectively. He is currently a Full Professor with the Department of Electrical and Computer Engineering, Khalifa University, United Arab Emirates. He has over 220 publications and three U.S. patents. He has been giving a number of international keynote speeches, invited talks, tutorials, and research seminars on the subjects of blockchain, the IoT, fog and cloud computing, and cybersecurity. He served as the Chair of the Track Chair of IEEE GLOBECOM 2018 on cloud computing. He is an Associate Editor of IEEE Blockchain TECH BRIEFS and a member of the IEEE Blockchain Education Committee. He is also leading a number of projects on how to leverage blockchain for healthcare, 5G networks, combating deepfake videos, supply chain management, and AI.

RAJAA JAYARAMAN received the bachelor’s and master’s degrees in mathematics in India, the Master of Science degree in industrial engineering from New Mexico State University, and the Ph.D. degree in industrial engineering from Texas Tech University. He is currently an Associate Professor with the Department of Industrial and Systems Engineering, Khalifa University, Abu Dhabi, United Arab Emirates. His expertise is in multi-criteria optimization techniques applied to diverse applications, including supply chain and logistics, healthcare, energy, environment, and sustainability. His postdoctoral research was centered on technology adoption and implementation of innovative practices in the healthcare supply chains and service delivery. He has led several successful research projects and pilot implementations in the area of supply chain data standards adoption in the U.S. healthcare system. His research interests include blockchain technology, systems engineering, and process optimization techniques to characterize, model, and analyze complex systems with applications to supply chains, maintenance operations planning, and healthcare delivery. His research has appeared in top-rated journals, including Annals of Operations Research, IIE Transactions, Energy Policy, Applied Energy, Knowledge-Based Systems, IEEE Access, Journal of Theoretical Biology, and Engineering Management Journal.

IBRAR YAQOOB (Senior Member, IEEE) received the Ph.D. degree in computer science from the University of Malaya, Malaysia, in 2017. He is currently working with the Department of Electrical Engineering and Computer Science, Khalifa University, United Arab Emirates. Previously, he worked as a Research Professor with the Department of Computer Science and Engineering, Kyung Hee University, South Korea, where he completed his postdoctoral fellowship under the prestigious grant of Brain Korea 21st Century Plus. He worked as a Researcher and a Developer with the Centre for Mobile Cloud Computing Research (C4MCCR), University of Malaya. His numerous research articles are very famous and among the most downloaded in top journals. He has been listed among top researchers by Thomson Reuters (Web of Science) based on the number of citations earned in the last five years in six categories of computer science. His research interests include big data, blockchain, edge computing, mobile cloud computing, the Internet of Things, healthcare, and computer networks. He is currently serving/serving as a guest/associate editor for various journals. He has been involved in a number of conferences and workshops in various capacities.

MOHAMMED OMAR is currently a Full Professor and the Founding Chair of the Department of Engineering Systems and Management (currently renamed Industrial and Systems Engineering). Prior to joining the Masdar Institute/KUST, he was an Associate Professor and a Graduate Coordinator with Clemson University, Clemson, SC, USA. He was a part of the Founding Faculty of Clemson University research park in Greenville, SC, USA. His professional career includes a postdoctoral service with the Center for Robotics and Manufacturing Systems CRMMS, and a Visiting Scholar with the Toyota Instrumentation and Engineering Division, Toyota Motor Company, Japan. His group graduated seven Ph.D. dissertations and over 35 M.Sc. theses. Four Ph.D. students are currently on academic ranks in U.S. universities. He has also led an NSF I/UCRC Center and a part of the DoE GATE Center of Excellence in Sustainable Mobility Systems. His current research interests include capabilities in composite fabrication and manufacturing analytics at the Laboratory Masdar City Campus. His current research group supported two Postdoctoral Scholar’s Career Planning to become an Assistant Professor with Texas A&M University (TAMU), in 2013, and the University of Sharjah, in 2015. He has over 100 publications in the areas of product
lifecycle management, knowledge-based manufacturing, and automated testing systems, in addition to authoring several books and book chapters. He holds four U.S. and international patents. He was named a Tennessee Valley Authority Fellow for two consecutive years during the Ph.D. degree, in addition to being a Toyota Manufacturing Fellow. His work has been recognized by the U.S. Society of Manufacturing Engineers (SME) through the Richard L. Kegg Award. He has also received the SAE Foundation Award for Manufacturing Leadership. In addition, he has received the Murray Stokely Award from the College of Engineering, Clemson University. He currently serves as the Editor-in-Chief for the Journal of Material Science Research (Part of the Canadian Research Center) and as an Associate Editor for the Journal of Soft Computing (Springer), handling the areas of decision science, knowledge-based systems, in addition to his membership on several editorial boards and conference organizations. Furthermore, he serves on the Advisory Board of the Strata PJSC (part of Mubadala Aerospace).

Samer Ellahham received the undergraduate degree in biology and the M.D. degree from The American University of Beirut, Beirut, Lebanon. He is currently a Cleveland Clinic Caregiver, Cleveland, USA, seconded as a Senior Cardiovascular Consultant and the Director of Accreditation with the Quality and Safety Institute, Cleveland Clinic, Abu Dhabi. He is also the Middle East Regional Chair; ISQua Expert, Patient Safety Movement Foundation; member, AHA Hospital Accreditation Science Committee; member, European Society of Cardiology Heart Failure Writing Group; ex-Middle East Representative of the JCI Standards Subcommittee; and member, American College of Cardiology Accreditation Foundation Board. He finished his internal medicine residency at Georgetown University Hospital–Washington Hospital Center and his fellowship in cardiology with the Virginia Commonwealth University Health System, USA, where he worked in Washington, DC, and in several clinical and leadership positions before moving to the United Arab Emirates, in 2008. He continues to be an active clinician. He demonstrates great skill and experience in the management of patients with heart failure, ischemic heart disease, and valvular heart disease. He has led a multi-disciplinary team in the care and delivery of advanced therapies to these patients. He has unique abilities to partner and engage local and regional referring providers. He can work in a highly matrixed environment, has strong leadership and organizational skills, and has the experience of working effectively in a large health system. He has worked as the Chief Quality Officer for SKMC, from 2009 to 2017. In his role, he has led the development of a quality and program that has been successful and visible and has been recognized internationally by several awards. As the Chief Quality Officer and the Global Healthcare Leader, he had a focus on ensuring that the implementation of these best practices leads to breakthrough improvements in clinical quality, patient safety, patient experience, and risk management. He was an Executive SKMC Sponsor of the American College of Surgeons National Surgical Quality Improvement Program (ACS NSQIP) the leading U.S. validated, risk-adjusted, outcomes-based program to measure and improve the quality of surgical care. SKMC is the first multispecialty ACS NSQIP Center outside the USA. He led the publication of, first in the region, annual SKMC outcome books, since 2011 and 2012; the Sheikh Khalifa Excellence Award, in 2014; the Quality Leadership Award from the World Quality Congress and Awards and the Business Leadership Excellence Award from World Leadership Congress, in 2015; one of the nominees for Safe Care Magazine Person of the Year in the United States; the Dubai Quality Award, in 2015; and the Sheikh Khalifa Excellence Golden Award, in 2015. He is also the Middle East Regional Chair of the Patient Safety Movement Foundation. He is an Eminent Editor of The Journal of Cardiology & Cardiovascular Therapy and an Associate Editor of the American Journal of Medical Quality. In addition, he serves on the editorial board of Journal of Thoracic Disease and Cardiothoracic Surgery, Developments in Clinical & Medical Pathology (DCMP), The Joint Commission Journal on Quality and Patient Safety, Telehealth and Medicine Today (TMT), Blockchain in Healthcare Today (BHTY), Medical Science, Open Journal of Cardiac Research, UPI Journal of Pharmaceutical, Medical and Health Sciences (UPI-JPMHS), Open Access Research in Anatomy, Gerontology & Geriatrics Studies and Open Access Journal of Clinical Trials, Hypertension Today Journal and Focus on Hypertension Journal, Journal of Heart Health, Cardiovascular Pharmacology, Scientific Research, and Community, Journal of Surgery and Surgical Procedures, EC Cardiology, Journal of Cardiovascular and Pulmonary Medicine, and Canadian Journal of Biomedical Research. He is also a reviewer for several peer-reviewed journals, including Joint Commission Journal on Quality and Patient Safety, International Journal of Quality & Reliability Management, the Journal of American College of Cardiology, the American Heart Journal, Annals of Internal Medicine, Archives of Internal Medicine, Chest, Circulation, Clinical Cardiology, The Lancet, Diabetes Care, Endocrinology and Metabolism, European Journal of Heart Failure, Congestive Heart Failure Journal, Journal of Nuclear Cardiology, Journal of Transplant Coordination, Journal of Cardiovascular Pharmacology and Southern Medical Journal, European Journal of Innovation Management, The Anatolian Journal of Cardiology and NPJ Digital Medicine. He enjoys volunteering, tennis, healthy lifestyle, innovation, teaching, and future health.