Trends in Biotechnology

CellPress

Forum

Sensors in blockchain

Alara Altay,[1,2] Robert Learney,[3] Firat Güder,[4,5,*,@] and Can Dincer[1,2,5,*,@]

Blockchain, the technology behind bitcoin, has stimulated global conversation around digital decentralization to connect societies and economies. Connected low-cost sensors within Internet of Things (IoT) networks may soon perform measurements, exchange data, and make decisions automatically over decentralized networks; these systems could improve healthcare, the quality of goods, and supply chain efficiency.

This article addresses the state-of-the-art and future applications of sensors combined with blockchain technologies (Box 1) for decentralized healthcare, storage, and quality control along a supply chain for food or pharmaceuticals. The use of low-cost (preferably disposable) sensors with security features could eliminate the need for testing by trusted third-party centralized laboratories/institutions, soon transforming healthcare and supply chain management [1] (Figure 1).

Healthcare

Electronic medical records (EMRs), primarily created through collating the results of diagnostic tests, involve many parties feeding data into these complex systems, making them susceptible to falsification (wittingly or unwittingly). Ensuring the integrity of data within these complex systems is expensive and slow because multiple professionals need to validate the entries. Absolute protection is needed against Byzantine faults (unpredictable errors with no clear information about them) to implement 'trust' in these systems. The principles of decentralization, cryptographic assurance, and verification behind blockchain make it suitable for managing EMRs, thus creating a decentralized 'trustless' ecosystem without storage at a centrally controlled location. In this scenario, individuals would own their medical data and be assured that their information is not misused because requests to access the data would also be stored and inalterable. This approach creates a new level of trust. Fast healthcare interoperability resources (FIHR, a standard for data formatting and exchange) provide medical data interoperability, and the ideas behind blockchain will return data sovereignty to patients themselves. Blockchain technologies will therefore empower patients to manage how their data is processed and shared between sites and authorities. A successful working example is Estonia's healthcare system where access and updates are secured by blockchain. This approach provides better communication among health professionals and leads to faster diagnosis and increased effectiveness in healthcare services (www.businessinsider.com/guardtime-estonian-health-records-industrial-blockchain-bitcoin-2016-3).

The increasing need for remote patient monitoring (RPM) has substantially accelerated recently owing to the COVID-19 pandemic. Because the development of tests and vaccines is slow, the detection of infectious diseases and monitoring of patients with health conditions can be supported by wearable (such as smartwatches, electronic patches or wristbands) and other point-of-care (e.g., glucometer or lateral flow assay) sensors [2,3]. These devices generate medical data remotely which can be shared with care providers, drug suppliers, and insurers across borders and systems when desired. Recently, blockchain-based smart contracts have been proposed to securely analyze and manage sensors, automate real-time RPM, analyze medical data, and observe the physical condition of a patient by healthcare professionals through digital notifications [4]. By implementing smart contracts, it is not far-fetched to imagine fully autonomous, trustless EMR systems integrated with RPM that can detect diseases and automate patient care. For instance, early detection of a disease using the data acquired by sensors can trigger a smart contract. This would subsequently begin the treatment, sending medications to the patient and billing to the insurer (where the payment may be performed by cryptocurrencies across borders). To keep the big data generated by the patients and sensors secure, blockchain-based technologies can be used for cryptographic storage and gated access through smart contracts [5].

Supply chains

One of the biggest problems in the pharmaceutical industry is to provide the necessary environmental conditions (i.e., an uninterrupted cold-chain) for delivering pharmaceuticals. For example, the Pfizer-BioNTech COVID-19 vaccine requires storage at −70°C, an extremely low temperature that makes its transportation difficult [6]. Connected sensors integrated in a blockchain-enabled network would allow trustless monitoring of pharmaceuticals where every step on the way from production to delivery could be traced.

Monitoring of pharmaceuticals across the supply chain has been primarily limited to measuring environmental conditions (temperature and humidity) during delivery. For example, the Swiss start-up Modum uses IoT-based sensor platforms with blockchain technology to provide data immutability and access to temperature records [7]. Each shipment is continuously monitored by sensors to comply with the Good Distribution Practice regulations of the European Medicines Agency. The sensor data received via Bluetooth are transferred to a blockchain, and any deviations are reported to the receiving party and distributor. The supply chain for

Box 1. Blockchain technology

The main idea behind blockchain is to enable a network of unknowing or untrusting parties to come to agreement on shared information, without requiring centralized verification or a trusted third party. Blockchain is a type of distributed ledger where the ledger records every transaction from the start until the end, and is put into a block. Blockchain implementations are generally immutable, meaning that once a block containing data is created, it cannot be changed or deleted. A similar analogy can be found in nature in the clustered regularly interspaced short palindromic repeats (CRISPR) sequences (a part of prokaryotic adaptive immune system) because they are derived from DNA fragments that infected the prokaryote beforehand (https://sitn.hms.harvard.edu/flash/2014/crispr-a-game-changing-genetic-engineering-technique/).

Once data is recorded on a blockchain, it would require an overwhelming majority of participants to collude to falsify history or amend entries. Mathematical tools are used to create a blockchain, including 'hashing' to uniquely fingerprint content. Changes to the data will change the hash, which makes the detection of any modification to blocks trivial. Moreover, some of the techniques for data management used in blockchain, such as hashing and Merkelization, allow easy verification of data without the need to access all records. A smart contract is an agreement between two parties that is written in computer code, stored, and executed across a decentralized network. Smart contracts ensure that the same algorithms execute for everyone and, again, cannot be easily tampered with. Due to the growing demand for Big Data and IoT, blockchain technology has recently been applied to areas other than finance, including supply chain management, contracts, healthcare, and insurance.

pharmaceuticals can benefit from chemical testing using low-cost sensors at various points in the chain to guarantee that what is being shipped and delivered are chemically identical. Such approaches would reduce the presence of counterfeit drugs in the market and ensure the chemical quality of pharmaceuticals, which continues to be a problem, especially in the developing world.

The issues concerning supply chain integrity for pharmaceuticals also apply to food. With the emergence of COVID-19, the supply chain for food products was heavily disrupted, exacerbating concerns for access to safe food. Sensing technologies, in combination with blockchain and smart contracts, could provide information about stock levels and their quality and shelf-life. Because the information on the blockchain can be instantly shared with government organizations, regulators (the FDA or the European Food Safety Authority) could closely monitor the health and efficiency of the supply chains and certify them. Recognizing the importance of safety, freshness, waste, and efficiency across the food system, IBM Food Trust has recently created the first blockchain food safety solution that allows transaction partners to confidently and securely share food information [8].

Various emerging disposable sensing technologies could be married with blockchain to monitor biological processes (including microbial activity) within food products. For instance, BlakBear, a London-based startup, is currently developing a low-cost electrical sensing technology [9] to monitor food quality in real-time (https://blakbear.com). Such systems could integrate into a blockchain network to enhance tamper protection, traceability, and safety within the supply chain.

Challenges

Sampling and sensing

In a decentralized system, where trusted third parties are eliminated, every process within the system must be trustless. It is generally straightforward to ensure the integrity of sensor data once digitized, but it is not trivial to guarantee sample and sensor performance. Imagine a scenario where a test result for a pharmaceutical product is pushed onto the blockchain, triggering a smart contract. If the test passes when performed by the receiving party, the sender gets paid, but if the test fails, the party receiving the goods gets a refund. However, nothing prevents the receiving party from using a bad sample from elsewhere to produce a negative result to receive a refund. Blockchain technologies alone cannot address the 'bad sample' issue, and additional research may be necessary to implement trust into sampling protocols.

In a trustless system that relies on sensors, the sensors used would still need to be trusted by all parties to reach consensus. Sensors must also produce results with high sensitivity, selectivity, accuracy, and long-term stability to ensure reliable results. Similarly to the 'bad sample' problem, the sensors themselves would need to be tamper-proof so that they could not be modified at will. In addition, blockchain technologies require an internet connection – in remote regions of the world internet infrastructure may not be widely available, reducing the usability of blockchain-enabled sensing solutions.

Digital data

Sensor data uploaded to a blockchain will need to conform to network-defined standards and follow network protocols. There is little standardization between different blockchain networks, and interoperability between networks (Ethereum and Hyperledger Fabric, etc.) is therefore currently low [10]. Solving this is an active area of research in the blockchain community.

The algorithmic rule of immutable blockchain does not comply with the EU General Data Protection Regulation which mandates that users have the right to demand their data to be completely removed from the system. Advances in cryptography may improve this situation, but for now the best advice is still to not place any user identifiable information into a public blockchain.

Sensors that generate large sets of data continuously would require a fast blockchain that is not only computationally inexpensive to reach consensus but is also able to store large volumes of data. In reality, such

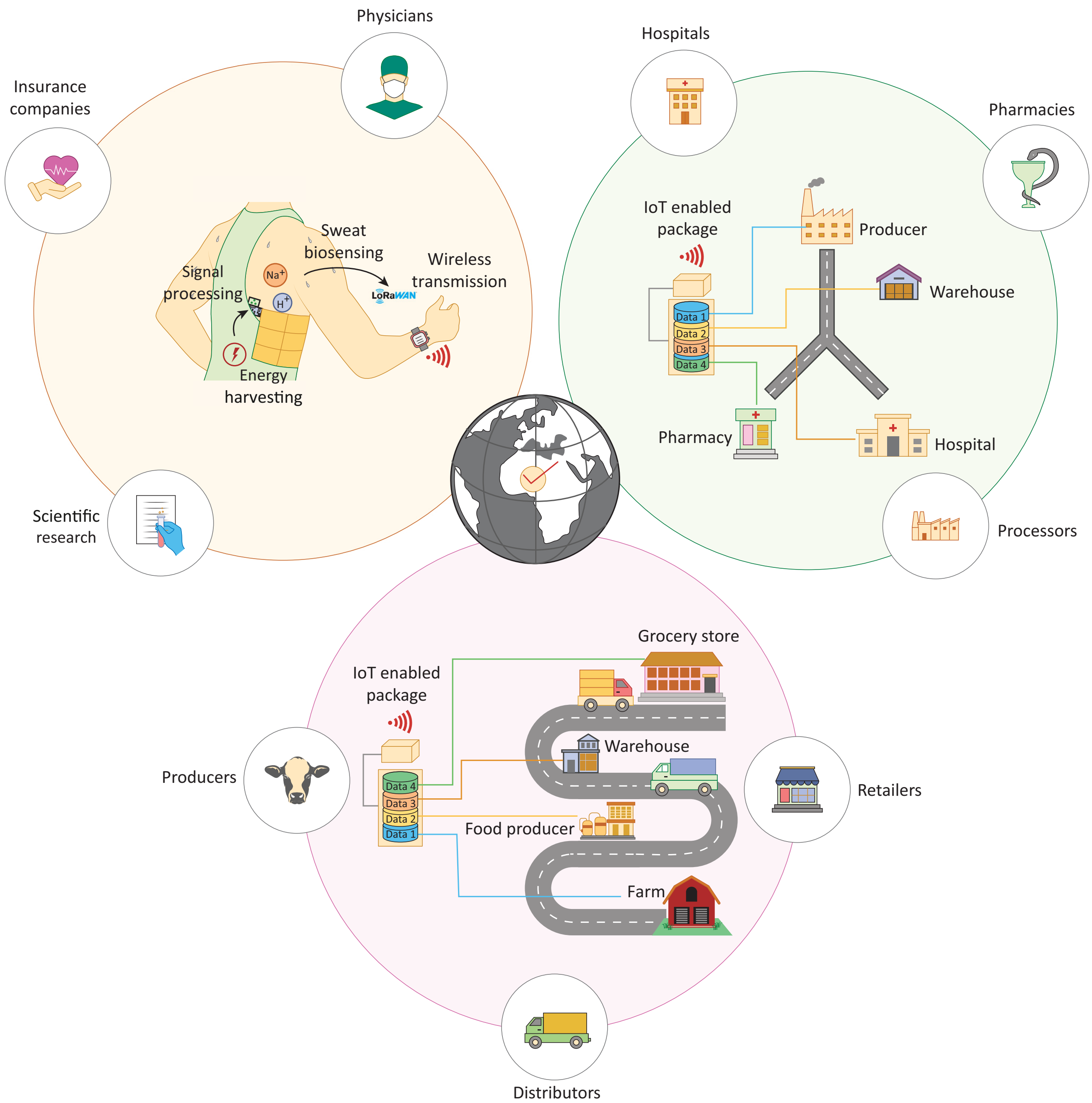

Figure 1. Application scenarios of sensors in blockchain. (A) Healthcare (wellness, diagnostic, and theranostic applications): the vital signs of the user are monitored by a wearable sensor (that is preferably capable of energy harvesting [14]), and the data generated are sent to a blockchain by wireless transmission. All parties that are allowed by the user can access the health data. With the implementation of smart contracts to make entries in electronic medical records, early detection of diseases using sensor data, delivery of appropriate drugs to the patient, billing to the insurer, and payment with cryptocurrencies can automatically be achieved. (B) Food and (C) pharmaceutical supply chains: Internet of Things (IoT)-enabled packages transmit information concerning their status while in transit. The conditions required during the shipment are agreed beforehand between the sender and receiver. Sensors embedded in the packages record the data and upload to the blockchain to share with both parties, potentially triggering smart contracts to automate transactions.

implementation would be difficult to create and maintain in a decentralized fashion to handle large datasets owing to storage and power requirements [11].

Users

Management of the sensors and their data on a blockchain will likely be challenging or impossible for older and very young populations who may either not be interested or are only able to participate in an emerging technology with a learning curve [10].

Outlook

For wide adoption of low-cost (bio)sensors combined with blockchain technologies for IoT applications, the challenges outlined should be rigorously addressed. For example, storage of large volumes of 'raw' data will likely require encrypted off-chain storage on the cloud [12], where only metadata or 'fingerprints' are logged onto a blockchain. The issue of continuous monitoring using wearables could be targeted by investigating energy harvesting for self-powered sensors such as biofuel cells (converting glucose in sweat using enzymes or using microbial fuel cells [13]) and human motion [14]. LoRaWAN® (long-range wide-area network) technology, instead of Bluetooth, might also be considered to create a low-power high-coverage wireless digital infrastructure for sensors in remote locations to interact with the blockchain network. LoRaWAN, however, will not be sufficient for truly remote regions which may require space-based technologies for communication. Blockchain and sensors can also be combined with other low-cost, high-security wireless and battery-free technologies such as near-field communication to extend capabilities and acquire information from locations that are otherwise inaccessible over long timescales [15]. Significant decreases in energy consumption of both IoT-enabled sensors and blockchain networks with new technologies can further reduce their carbon footprint.

Further research to address the challenges of blockchain technology, in conjunction with low-cost sensors, will provide countless new opportunities to improve healthcare, ensure the quality of goods, and create efficient and reliable supply chains.

Acknowledgments

This research has been partially funded by Deutsche Forschungsgemeinschaft (DFG, German Research Foundation; grants 404478562 and 421356369) and the US Army (contract W911QY20P0280).

Declaration of interests

The authors declare no conflicts of interest.

[1]University of Freiburg, Freiburg Center for Interactive Materials and Bioinspired Technologies (FIT), 79110 Freiburg, Germany
[2]University of Freiburg, Department of Microsystems Engineering (IMTEK), Laboratory for Sensors, 79110 Freiburg, Germany
[3]Digital Catapult, London NW1 2RA, UK
[4]Imperial College London, Department of Bioengineering, Royal School of Mines, London SW7 2AZ, UK
[5]Equal contributions

*Correspondence:
f.guder@imperial.ac.uk (F. Güder) and
dincer@imtek.de (C. Dincer).
@Twitter: @ImtekSensors (C. Dincer) and @gudeResearch (F. Güder).

https://doi.org/10.1016/j.tibtech.2021.04.011

References

1. Dincer, C. *et al.* (2019) Disposable sensors in diagnostics, food, and environmental monitoring. *Adv. Mater.* 31, 1806739
2. Ates, H.C. *et al.* (2021) Wearable devices for the detection of COVID-19. *Nat. Electron.* 4, 13–14
3. Seshadri, D.R. *et al.* (2020) Wearable sensors for COVID-19: a call to action to harness our digital infrastructure for remote patient monitoring and virtual assessments. *Front. Digit. Heal.* 2, 8
4. Griggs, K.N. *et al.* (2018) Healthcare blockchain system using smart contracts for secure automated remote patient monitoring. *J. Med. Syst.* 42, 130
5. Saravanan, M. *et al.* (2017) SMEAD: a secured mobile enabled assisting device for diabetics monitoring. In *2017 IEEE International Conference on Advanced Networks and Telecommunications Systems (ANTS)*, pp. 1–6, IEEE
6. Crommelin, D.J.A. *et al.* (2020) Addressing the cold reality of mRNA vaccine stability. *J. Pharm. Sci.* 110, 997–1001
7. Bocek, T. *et al.* (2017) Blockchains everywhere – a use-case of blockchains in the pharma supply-chain. In *2017 IFIP/IEEE Symposium on Integrated Network and Service Management (IM)*, pp. 772–777, IEEE
8. Park, A. and Li, H. (2021) The effect of Blockchain technology on supply chain sustainability performances. *Sustainability* 13, 1726
9. Barandun, G. *et al.* (2019) Cellulose fibers enable near-zero-cost electrical sensing of water-soluble gases. *ACS Sensors* 4, 1662–1669
10. Kamel Boulos, M.N. *et al.* (2018) Geospatial blockchain: promises, challenges, and scenarios in health and healthcare. *Int. J. Health Geogr.* 17, 25
11. Yli-Huumo, J. *et al.* (2016) Where is current research on Blockchain technology? A systematic review. *PLoS One* 11, e0163477
12. Esposito, C. *et al.* (2018) Blockchain: a panacea for healthcare cloud-based data security and privacy? *IEEE Cloud Comput.* 5, 31–37
13. Song, Y. *et al.* (2021) Self-powered wearable biosensors. *Acc. Mater. Res.* 2, 184–197
14. Song, Y. *et al.* (2020) Wireless battery-free wearable sweat sensor powered by human motion. *Sci. Adv.* 6, eaay9842
15. Olenik, S. *et al.* (2021) The future of near-field communication-based wireless sensing. *Nat. Rev. Mater.* 6, 286–288