

# Scaling Blockchains to Support Electronic Health Records for Hospital Systems

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**Abstract**—Electronic Health Records (EHRs) have improved many aspects of healthcare and allowed for easier patient management for medical providers. Blockchains have been proposed as a promising solution for supporting Electronic Health Records (EHRs), but have also been linked to scalability concerns about supporting real-world healthcare systems. This paper quantifies the scalability issues and bottlenecks related to current blockchains and puts into perspective the limitations blockchains have with supporting healthcare systems. Particularly we show that well known blockchains such as Bitcoin, Ethereum, and IOTA cannot support transactions of a large scale hospital system such as the University of Kentucky HealthCare system and leave over 7.5M unsealed transactions per day. We then discuss how bottlenecks of blockchains can be relieved with sidechains, enabling well-known blockchains to support even larger hospital systems of over 30M transactions per day. We then introduce the Patient-Healthchain architecture to provide future direction on how scaling blockchains for EHR systems with sidechains can be achieved.

**Index Terms**— *Blockchain, Telehealth, Electronic Health Records (EHRs), Electronic Medical Records (EMRs), Healthcare, Scalability, Sidechain, Distributed Systems, Access Control Lists*

## I. INTRODUCTION

The healthcare industry has come a long way from the days of keeping paper records and using fax machines as a primary source of communication. Now there are Electronic Health Records (EHRs), which are digital translations of a patients paper chart [1], [2]. EHRs were created with the intention of not only containing the treatment information of patients, but to also facilitate the quality of the care process. EHRs are capable of sharing information with other providers and organizations involved with a patients care [3].

EHRs, although an improvement upon the method of keeping paper copies of health records, are still a headache for medical providers [4]. Hospitals use different EHR software<sup>1</sup> which leads to a lack of *interoperability*, “the ability of different information systems to connect in a coordinated manner across organizational bounds” [5], across all medical facilities [4]. The lack of interoperability poses an issue in the case of

a patient whose treatment spans across multiple geographic locations or medical facilities [1]. When transferring between locations of treatment, the information that would be readily available at one location will not necessarily be available at a second location. Not having patient information promptly available could result in wasted resources due to the second location having a requirement to run tests on a patient that were already ran at the first facility.

Another limitation with the current EHR process is patient access, as patients do not have immediate access to their complete EHR. In addition, providers do not need to ask for patient consent to share information for a patient’s general care in the case of transfers. Not requiring consent means a patient will not always know who is accessing their health records [6]. For patients, having quick access to a complete health record would not only keep them aware but also mitigate concerns about who is accessing and making changes to their EHRs.

EHRs have improved quality of care and made record management easier for medical providers [7] and APIs have been developed for EHRs. For example, the Health Level 7 (HL7) standard Fast Healthcare Interoperability Resources (FHIR) is a RESTful open standard that has been adopted by many organizations. FHIR provides a simple and consistent structure for health data across platforms [8], [9]. Though FHIR greatly assists with the translation of data, there are still obstacles to overcome when it comes to privileges, access, accountability, and logging between hospital systems [10].

In the U.S., EHRs have to be in compliance with the *Health Insurance Portability and Accountability Act* (HIPAA) regulations making the handling and transferring of health data a security risk. HIPAA regulations require that entities implement safeguards that protect the confidentiality, integrity, and availability of EHRs of patients [11]. Blockchains use cryptographic technologies to ensure confidentiality even on a public blockchain. Integrity of data is kept through chronological hashes on an immutable ledger, which also allows for the availability of information.

From the perspective of a medical professional, EHRs allow for easier management of the large amount of patients that a medical provider deals with on a regular basis. However, from a patient’s perspective, there is still more work to be

<sup>1</sup>B. Siwicki, “Biggest EHR challenges for 2018: Security, interoperability, clinician burnout,” *Healthcare IT News*, 2017, <https://www.healthcareitnews.com/news/biggest-ehr-challenges-2018-security-interoperability-clinician-burnout>, Accessed: 10/3/19

done to improve how they are able to manage and keep track of all of their health records. Blockchains have been proposed [12]–[15] as a promising solution to managing EHRs, but have been known to have scalability issues [16]–[18]. This paper will quantify the scalability concerns with using blockchains for EHRs and discuss solutions to relieve the potential bottlenecks. The contributions of this work are to:

- quantify and put into perspective the scalability issues related to current blockchains
- discuss how to relieve bottlenecks using sidechains and highlight considerations
- propose the Patient-Healthchain architecture that uses sidechains and the Proof of Authority (PoA) consensus scheme to allow for high throughput and scalability

The remainder of the paper is structured as follows: Section II discusses relative preliminary information about aspects of blockchain technologies, Section III discusses the related work, Section IV discusses the benefits of sidechains for EHRs, Section V describes the proposed architecture, and Section VI concludes and mentions possible future work.

## II. BLOCKCHAIN PRELIMINARIES

One of the most well known uses of blockchain technology is Bitcoin [19]. Bitcoin is a cryptocurrency that attempts to decentralize the payment system. It removes the middle man of a financial institution and implements a peer-to-peer distribution of funds. Not needing a middle man is achieved through the use of Proof of Work (PoW) and a ledger that stores a list of all transactions made via the blockchain.

A *transaction* in a blockchain is an event that takes place and is then recorded on the blockchain. All nodes in the network race to verify that these transactions are correct, creating a system of trust in an innately trustless environment. A block is made up of a certain number of transactions before it is eventually mined to the blockchain. In the case of Bitcoin, a transaction is equivalent to a financial transaction.

### A. Notable Consensus Schemes

A consensus scheme is a way to validate a mined block before adding the block to the blockchain [20]. PoW and Proof of Stake (PoS) are two well known consensus mechanisms used by Bitcoin and Ethereum respectively [20], [21]. PoW has been described as a “cryptographic block-discovery racing game” [20]. In the case of Bitcoin, miners compete for bitcoin currency by solving hard hash puzzles that allow them to publish a block to the blockchain. The downside to PoW is that a lot of computing power is needed to solve the puzzles, which requires a huge electrical energy expenditure.

PoS was introduced to overcome the limitations of PoW [21]. To achieve PoS, a miner’s stake in the blockchain determines their mining power. Stake is determined by factors such as wealth or age in the blockchain, combined with random selection. A user who has been randomly selected as a validator will generate blocks at that given time. PoS

reduces the energy and computing power needed to maintain PoW.

An alteration of PoS is Delegated Proof of Stake (DPoS), which is used by BitShares [22]. DPoS uses *witnesses* and *stakeholders* to validate and generate blocks. Stakeholders vote on witnesses to generate blocks in a round table fashion. If a witness does not perform as expected, the stakeholders can vote them out, allowing someone else to become a witness. This model allows for a more decentralized consensus process. DPoS does not require participation in block generating from all users in the network, which allows for less computing power than PoS.

PoA [23] requires that a user who wants to be allowed to validate and generate blocks must request to do so. In order to get approved, a process is undertaken to verify identity. An example of this process would be getting a public notary to confirm an identity. Instead of solving complex math problems like in PoW, nodes in the network are designated as *authorities* and only those authorities are allowed to generate and validate new blocks [24].

Choosing the right consensus scheme is critical to producing a viable blockchain for use in healthcare. Traditional consensus schemes such as PoW or PoS may be suitable for a number of cases, but may not provide the best benefits for health systems. Properties to determine the correct consensus scheme for a medical blockchain should consist of the following: low power consumption, throughput consistent with the average healthcare system, and scalability [25].

### B. Smart Contracts

A smart contract is a self running script that is coded onto the blockchain. Smart contracts automatically execute when the required conditions defined in the code are met. Examples of these conditions are contractual terms being met, or a change in state [26]. A popular analogy used to describe smart contracts has been the vending machine comparison. When a person puts money into a vending machine, the person will either receive what they attempted to buy, or there will be an error and that person will get their money back.

While popular use of smart contracts started with Ethereum [27], smart contracts have already been implemented across many decentralized applications in various ways. Examples of smart contract applications include: defining trading criteria, access control, supply chain quality management, business process management, voting systems and identity management [26]. In the context of medical applications, smart contracts can be used as an access control mechanism [28].

### C. Sidechains

A sidechain is a blockchain separate from the parent blockchain or mainchain, connected via a two-way link [29] demonstrated in Figure 1. Sidechains offer the ability to offload tasks from the parent blockchain to the sidechain. Sidechains have been used in Bitcoin; referred to as Altchains,

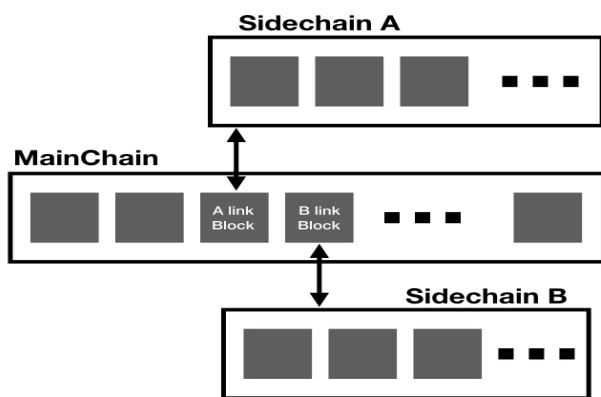


Fig. 1. Mainchain and Sidechain Relationship

and are used as a method to link and exchange other cryptocurrencies with bitcoins. Sidechains also allow for testing of features before attempting to implement them to the mainchain. One point to note about sidechains is that they operate as their own blockchain and therefore may require separate minors based on the selected consensus scheme.

Sidechains can also be used to complement a parent blockchain. A newer blockchain technology that utilizes sidechains is Aelf [30]. Aelf takes advantage of multiple chains to improve the efficiency of their blockchain, which allows for parallel processing of non-competing transactions. Sidechains could be the key to achieving scalability, which is essential for a blockchain purposed for healthcare. This is due to the fact that the load that would normally be present on one main blockchain could get distributed over the different sidechains, which in turn would reduce the possibility of a bottleneck effect occurring on the blockchain network.

### III. RELATED WORKS

MedRec [12] proposed and deployed a “decentralized record management system to handle EHRs, using blockchain technology”. The MedRec open source technology allows patients to achieve ease of access to their health records across providers and locations. MedRec’s permissionless architecture is based off of Ethereum [27], a well known application of blockchain. MedRec also touches on using the idea of *data economics* as an incentive for mining. In contrast, the blockchain discussed in this paper is permissioned and not dependent on a cryptocurrency.

MeDShare [13] is another blockchain application that focuses on the aspect of medical data sharing and the malicious actions that could occur with big data entities and data custodians [31]. MeDShare’s approach primarily focuses on when data is being queried and the tracking of all patient data associated with the blockchain. MeDShare also implements a way to categorize data sensitivity levels using smart contracts. The authors claim to have a tamper proof data audit and a way to revoke access to data that most blockchain solutions do not have. Unlike the blockchain in this paper, MeDShare’s target

users are not patients, and user interaction with MeDShare is merely for data requests.

Another proposed framework [14] analyzes aspects of Ethereum and Hyperledger [32] and the different services they offer that could be used towards the implementation of a “secure and trustable” EHR solution using blockchain. In [14] the application focuses on cancer patients and the authors’ propose a permissioned blockchain that also utilizes smart contracts to control access to data. The authors proposed blockchain uses the Practical Byzantine Fault Tolerance (pBFT) consensus protocol which becomes challenging to scale as more nodes are added to the network. The PoA consensus scheme used in Patient-Healthchain should significantly reduce scalability issues.

Liu *et al.* [15] developed the Blockchain based Privacy-Preserving Data Sharing (BPDS) for EHRs. BPDS identifies a different way to control patient privacy outside of the regular access control mechanisms using a content extraction signature (CES). The CES allows patients to censor their medical data of identifying information before sharing with other entities. Patient-Healthchain does not utilize any access control algorithm at the moment and relies on the EHRs being HIPAA compliant with data sharing. Although DPoS utilizes less resources to add blocks to the blockchain, the PoA consensus scheme discussed in this paper should provide faster block generation.

### IV. RELIEVING THE BLOCKCHAIN BOTTLENECK FOR LARGE SCALE HEALTH CARE SYSTEMS

While the idea of using blockchain technology in healthcare is not new, there are still obstacles that need to be overcome in order for blockchains to be used in such a large scale environment. Approaches have already been proposed in [13]–[15] and some have implemented such as in [12]. An important benefit of sidechains is the ability to register transactions and mine blocks simultaneously with other sidechains and the parent blockchain. The combination of blockchains and sidechains favor healthcare systems because at any given time there are multiple patient transactions occurring. The nature of blockchains requires multiple nodes in the network to come to consensus before generating a block, resulting in an eventual bottleneck in large scale systems. Using sidechains that are specific to an individual/patient in the network can impede the aforementioned bottleneck on the main blockchain for the following reasons:

- 1) Less transactions would be sent to the mainchain at any given time.
- 2) Transactions related to a patient would get added to that respective patient’s sidechain, therefore the occurrence of transactions regarding different patients are independent of each other.
- 3) A larger number of transactions could be handled across the network at any given time.

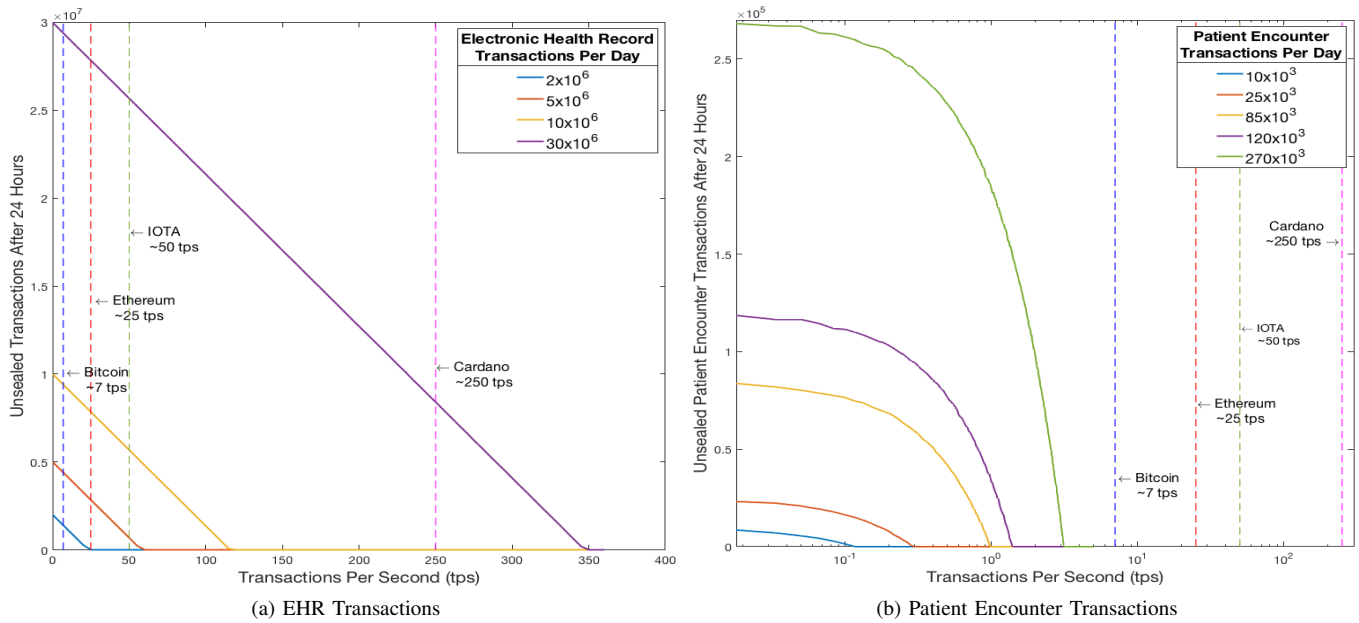


Fig. 2. Unsealed Transaction Comparisons

### A. Relieving the mainchain of cumbersome transactions

In Fig. 2, blockchain transactions were simulated to demonstrate the current limitations of traditional blockchains and how the utilization of sidechains can overcome the problem of bottlenecks when scaling up to the throughput of large medical systems. In these simulations, Poisson distributions, which models the variation in the number of discrete occurrences over a defined interval, were assumed. The assumption that a Poisson distribution should be used dates back to the original blockchain paper by Satoshi Nakamoto [19] and has been frequently used since [33]. Transactions were generated every second corresponding to the indicated average number of transactions per day. A *sealed* transaction is a transaction that has been added to a successfully hashed block on the blockchain. Whereas, an *unsealed* transaction is a transaction that is waiting to be added to a block on the blockchain. The abscissa corresponds to the rate per second for sealing transactions into blocks on the blockchain. The ordinate axis corresponds to the number of unsealed transactions at the end of a 24 hour period for a given rate of sealing transactions per second. Note, the plot of the simulations decrease linearly with the number of sealed transactions per second. Where the plot reaches the x-axis indicates the rate of sealing transactions necessary to handle the throughput for a given average rate of generating transactions.

Fig. 2a shows the results if every computerized transaction for an electronic health record system were sealed in blocks on the main blockchain.<sup>2</sup> This is equivalent to traditional

<sup>2</sup>S. O’Neal, “Who Scales It Best? Inside Blockchain’s Ongoing Transactions-Per-Second Race,” Cointelegraph, 2019, <https://cointelegraph.com/news/who-scales-it-best-inside-blockchains-ongoing-transactions-per-second-race>, Accessed: 10/3/19

blockchains attempting to handle all transactions. According to University of Kentucky (UK) HealthCare,<sup>3</sup> the average number of computerized transactions for a large medical system is approximately 10 million per day. Neither Bitcoin, Ethereum, or IOTA can handle the throughput of a system this large as they currently support 7 tps, 25 tps, and 50 tps respectively. When looking at Ethereum in Fig. 2a, it can be seen that when attempting to seal the 10M transactions of the UK HealthCare system, over 7.5 transactions are left unsealed at the end of each day. The largest number of EHR transactions per day that this study found in a real-world setting was 30 million per day<sup>4</sup>, for which Bitcoin, Ethereum, IOTA, and Cardano leave a substantial number of transactions unsealed at the end of a 24 hour period. Ethereum, becomes a viable option only after the throughput drops below approximately 2 million transactions per day. One might think to increase the block sizes or create more frequent block events to increase transaction throughput, but this results in more conflicts between blocks and reduces the level of security from attacks [34].

Fig. 2b shows the results if individual patient encounters were used as transactions on the main blockchain. A patient encounter transaction includes any in-patient discharge summary, any out-patient doctor visit or surgery. The x-axis is plotted on a logarithmic scale because the range of the

<sup>3</sup>L. Dawahare, “UK HealthCare Exploring Ways Big Data Analytics Can Improve Patient Care,” UK College of Medicine, 2015, <https://med.uky.edu/news/uk-healthcare-exploring-ways-big-data-analytics-can-improve-patient-care>, Accessed: 10/3/19

<sup>4</sup>N. Morris, “Change Healthcare: enterprise blockchain with 30 million transactions per day,” Ledger Insights, 2019, <https://www.ledgerinsights.com/change-healthcare-enterprise-blockchain-with-30-million-transactions-per-day/>, Accessed: 10/3/19

TABLE I  
NUMBER OF SIDECHAINS NEEDED

Number of Patients	Number of Transactions Per Day	Number of Sidechains Needed			
		Bitcoin	Ethereum	IOTA	Cardano
1	110	1	1	1	1
1,000	110,000	1	1	1	1
10,000	1,100,000	2	1	1	1
50,000	5,500,000	10	3	2	1
100,000	11,000,000	19	6	3	1
200,000	22,000,000	37	11	6	1
300,000	33,000,000	55	16	8	2

number of patient encounters per second in real healthcare systems span several orders of magnitude. Kaiser Permanente, one of the largest healthcare systems, 2018 Annual Report shows they have 47M doctor visits a year [35]. Another report says Kaiser Permanente has over 100M patient encounters with physicians a year<sup>5</sup>. 40M patient encounters and 100M doctor visits translates to approximately 128,767 and 273,973 patient encounters per day, respectively. The slowest of the blockchains; Bitcoin and Ethereum can handle the throughput of several healthcare systems the size of Kaiser if only encounters are maintained on the main blockchain. Here, we assume transactions related to inputting data to individual patient records can be handled by sidechains which is what is proposed in Section V.

### B. Scaling with sidechains

A natural succeeding question is, “how many sidechains should be generated to support mainchains for EHR systems?” The amount of sidechains needed is not easy to answer as the type of sidechain and respective consensus mechanism selected significantly impact the resources needed to operate. Table I provides insight into how sidechains might handle the bandwidth of transactions depending on how many patients are placed on a sidechain. We do not propose a particular type of blockchain be used for sidechains, but instead show the amount of patients some traditional blockchains can support.

To determine the average amount of transactions per patient per day, we use the 30M transactions mentioned earlier and divide it by the total number of patient encounters at Kaiser Permanente per day, 273,973, to get ~110 transactions. Note that this is most likely an overestimate for many hospital systems as we used the largest amount of transactions found and patient encounters for a large hospital system such as Kaiser. If the amount of transactions per patient per day for a particular hospital system ends up being less than 110, a lower amount of sidechains will be needed than displayed in Table I. We also assume that each of the 100M patient encounters reported by Kaiser Permanente per year is a unique patient, which may not necessarily be true.

## V. PATIENT-HEALTHCHAIN ARCHITECTURE

This section of the paper covers the Patient-Healthchain architecture that uses sidechains for Healthcare systems. Patient-

<sup>5</sup>D. Barkholz, “Kaiser Permanente chief says members are flocking to virtual visits,” Modern Healthcare, 2017, <https://www.modernhealthcare.com/article/20170421/NEWS/170429950/kaiser-permanente-chief-says-members-are-flocking-to-virtual-visits>, Accessed: 10/3/19

TABLE II  
TRANSACTIONS

Transaction Types	Members	Chain
Joining/Leaving the network.	Hospital/Patient	Mainchain
End of patient interactions/visit that produce discharge summaries	Hospital/Patient	Mainchain, Sidechain
Information sharing with other hospital systems in the consortium	Hospital	Sidechain
Health records being accessed by a new entity	Patient	Sidechain
New diagnoses from medical staff/Changes in health records	Hospital/Patient	Sidechain
Financial requests/Transactions	Hospital/Patient	Sidechain

Healthchain allows patients to have one central place to access all their medical information regardless of the underlying system different hospitals use. Having a system that appears uniform to the patient should help improve the overall perception about technology for healthcare.

### A. Blockchain Members and Transactions

Patient-Healthchain is a private permissioned blockchain, also known as a consortium blockchain. In a permissioned blockchain only members of the consortium (e.g. hospitals) and users that consortium member permits (e.g. patients) will be able to join the blockchain. For the scope of this paper, blockchain members are hospitals and users are patients, future work might determine that it is beneficial to allow researchers or insurance adjusters as members or users.

In Patient-Healthchain, a transaction can be the record of any interaction between a patient and their medical provider, an interaction between hospital systems, or a change to a patient’s health record. When a member joins or leaves Patient-Healthchain, it is also recorded as a transaction. Depending on the type of transaction, a transaction will either get published to the main blockchain or to a hospital/patient sidechain. Specific transactions are outlined in Table II.

### B. Mainchain-Sidechain Relationship and Block Structure

Fig. 3 depicts the Patient-Healthchain Architecture and the relationships between entities in the network. Patient-Healthchain assumes that patients interact with hospitals that do not naturally communicate with each other. Individual hospital systems can, however, communicate with the blockchain network, enabling them to interact with each other. Patients will also be able to interact with hospitals through the blockchain network. The structure of Patient-Healthchain consists of a “mainchain” and multiple “sidechains”. A sidechain is assigned to its respective member when the member initially joins Patient-Healthchain. When a patient joins the blockchain network a link is created between the patient’s initial block on the mainchain and their newly created sidechain; the same process occurs when a hospital joins the network. The purpose of a patient member’s sidechain is to retain all information relevant to a specific patient’s medical lifecycle. A hospital’s sidechain functions as a standalone blockchain for the hospital system.

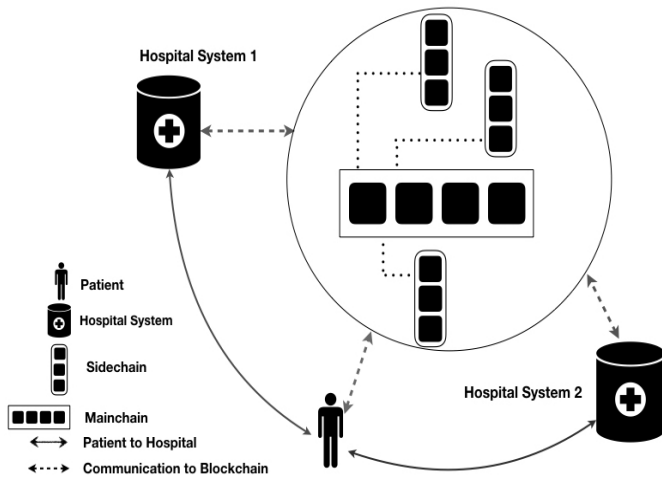


Fig. 3. Architecture Overview

Fig. 4 shows the types of data that makes up a block in Patient-Healthchain. A block could be composed of multiple transactions. The *block header* is the hash of the header of the preceding block. *Transactions* consist of recorded information between members and have the following attributes:

- Transaction ID — identifies the transaction and link same transactions between mainchain and sidechains.
- Hash of data — used to verify that the data being accessed (usually patient medical information) has not been tampered with.
- Path — path to related data (access purposes)
- Timestamp — time that the related transaction occurred.
- Signatures — signatures from related parties to verify that data is accurate. (e.g. patient, doctor)
- Access Control List (ACL) — managed by smart contracts, will contain a list of permitted public keys that are authorized to access information related to the respective transaction.

The block *timestamp* will refer to the time that the block was created. The block *signature* is the signature of the validating node who published that block. Block structures remain consistent on both the mainchain and the sidechains.

### C. Proof of Authority for Patient-Healthchain

As discussed in Section II-A, in order to choose a fitting consensus scheme for a blockchain used in healthcare, the following should hold: the consensus scheme should not consume a lot of power, throughput to the blockchain should be able to keep up with the average throughput of a healthcare system, resulting in a blockchain that scales to large system use. A consensus scheme that consists of the aforementioned characteristics is PoA. The PoA consensus scheme can work well for blockchains in healthcare systems for a number of reasons, including:

- 1) Validator’s identities can be checked and confirmed by public notaries. Confirming an identity ensures that a

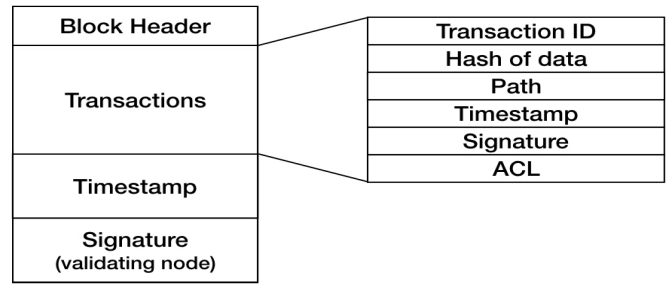


Fig. 4. Block Overview

member is who they say they are and that the member will be completely liable for actions that could jeopardize the privacy and security of the blockchain.

- 2) The blockchain is private, therefore it is only possible for members of the consortium to be able to become a validator and generate blocks.
- 3) Due to the nature of the data that is being shared over the blockchain, patient trust and the trust between other consortium members would increase knowing that any bad actor in the blockchain network can be easily identified and reprimanded.
- 4) The throughput of a blockchain for healthcare should be equal to or faster than what a patient or provider expects/needs in comparison to the current system in place. PoA removes the computation component of other consensus mechanisms and allows for almost immediate generation of blocks to the chain.
- 5) PoA also allows for the absence of cryptocurrency on the blockchain. The incentive for use is the overall ease of patient data sharing across multiple facilities, e.g. increased interoperability, which has proven to be an issue for providers [36].

### D. Patient Consideration for EHRs

Patient-Healthchain aims to put access control of records in the hands of patients as well as help integrate different EHRs at the provider level. EHRs should also always be up-to-date and readily available to the patients. There has been advancement in this area, for example early in 2018 Apple announced that 12 hospitals were participating in merging their EHRs with Apples Health Records app<sup>6</sup>. Patients are able to synchronize EHR data from multiple healthcare systems to their phone for ready access. However, the data synchronized into the Health Records app is not available for providers, accordingly if a patient wants to share information from one health care system to another they must manually show their

<sup>6</sup>Apple Inc., “Apple announces effortless solution bringing health records to iPhone,” Apple Newsroom, 2018, <https://www.apple.com/newsroom/2018/01/apple-announces-effortless-solution-bringing-health-records-to-iphone/>, Accessed: 10/3/19

data to providers<sup>7</sup>.

Facilitating the transfer of information between providers using different hospital systems can be handled using the proposed Patient-Healthchain architecture. A patient's respective sidechain provides them with the ability to see their whole EHR along with controlling the providers who have access to their information. Access control is handled through an authorized list of provider keys that are updated via smart contracts whenever a patient grants or revokes access. Patients are able to see when providers are requesting and sharing information, and if their provider changes, the patient can also choose to revoke access to their data.

## VI. CONCLUSION

This paper quantifies and puts into perspective the bottleneck problem that could occur when trying to use a single blockchain to handle multiple healthcare systems and their patients due to the inability for current blockchain architectures to keep up with the output of transactions in healthcare. We also propose relieving bottlenecks on the blockchain by using sidechains. Lastly, the Patient-Healthchain architecture is proposed as an advancement towards solving the EHR interoperability problem and the issues surrounding a bottleneck. Future work will explore the types of workload being placed on the sidechains, particularly when it comes to different consensus schemes and the burden placed on miners that results in energy consumption.

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