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Published Version:
Blockchains' federation: Developing Personal Health Trajectory-centered health systems / Rojo, J; García-Alonso, J; Berrocal, J; Foschini, L; Bellavista, P; Hernández, J; Murillo, JM. - ELETTRONICO. - (2023), pp. 81-88. (Intervento presentato al convegno 2023 IEEE/ACM 23rd International Symposium on Cluster, Cloud and Internet Computing Workshops (CCGridW) tenutosi a Bangalore, India nel May 1-4, 2023) [10.1109/CCGridW59191.2023.00027].

This version is available at: https://hdl.handle.net/11585/953976 since: 2024-01-27

Published:

DOI: http://doi.org/10.1109/CCGridW59191.2023.00027

Blockchains' federation: Developing Personal Health Trajectory-centered health systems

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***Abstract*—The current world is a globalized and connected one. Even without moving around, a person interacts with personnel from different institutions treating him as a patient in their daily life. Each of these institutions keeps their patients' data stored in their own information system, in an isolated way. Due to this, each patient has their data scattered among all these institutions and services with which she interacts along her life. This can complicate the take of the proper decision when the patient is under treatment. To solve this situation, new patient-centered health systems have been proposed as a replacement to the actual institution-centered ones, storing all health information of a patient into a unique global vision. However, some questions have arisen around the actual proposals, as who should store and maintain this vision of a given patient, and how should this information be made available for other systems. The proposal presented in this paper advocate for the achievement of a Personal Health Trajectory that can be useful both for patients and health professionals, using the concept of blockchains' federation. The proposal has been validated using 5689 records from 50 different institutions, belonging to 1156 actors.**

***Index Terms*—Data integration, Data interoperability, health data, Blockchain, Web Services**

I. Introduction

Far away is traditional medicine where all the procedures and their related data were documented on paper. Over the decades, digitalization has arrived for all domains, including healthcare. This has allowed us to adopt the advantages of digital support on all-around health processes, such as computer-assisted treatment [1], the better documentation of information involving a treatment, and a more efficient storage and management of health data. In the last, different improvements have been done, defining more complex structures for the digital representation of healthcare information.

Although in the early days the use of resources such as the now widely used Electronic Health Records (EHRs) [2] was sufficient to digitally represent a patient's health data, with the increasing penetration of smart Internet of Medical Things (IoMT) devices [3], [4] that also collect patient health-related data, the use of new resources or standards has become necessary. The sources constantly generating patient data are becoming larger and more varied. As technology strives to be able to collect all this information and digitize it, new resources such as Personal Health Records (PHRs) [5] have emerged in recent years. The broader term PHR already contemplates that a patient's health information can be generated inside or outside a hospital, even by smart devices [6].

However, although the effort done to produce health data digitalization advances is commendable, it is not enough. Until now, advances in digitalization have helped institutions to keep their patients' data organized and presenting a great value for the institution and for the patients themselves. Nevertheless, each institution and connected service generating data from the patient keep storing it in their own information systems. So, if a patient interacts with different institutions or uses different IoMT devices to measure her health [7], her health data is going to be dispersed.

Due to the intrinsic institution-centered nature of most of the actual health systems, each institution and service of IoMT devices storing its patients' data in an isolated way can seem the most suitable one. In this way, each institution and service keeps the control over the data they generate. While this is desirable for institutions, it has also a series of implications from the patient's perspective, since this causes that each of them has different representations of her health reality. This means that the information stored in each of them is a candidate to be potentially inconsistent. So, the above-mentioned benefits of digitalization are now mitigated [8].

That's the reason why many proposals have arisen during the last few years, trying to integrate or make interoperable the data of patients, stored in current institution-centered health systems, and bringing society closer to new patient-centered healthcare systems. Even more due to the expansion of novel technologies, such as blockchain. While some of the proposals recommend the use of classic solutions, such as cloud-based architectures [9], [10], most make use of blockchain [11]–[13], due to its distributed nature, as well as its guarantees on data security and privacy [14]. Blockchain is being used in different parcels of eHealth, and the integration of distributed health data is precisely one of the most highlighted [15].

Despite the technology employed, current proposals can be distinguished into two main types. First, proposals that try to physically integrate the data of each patient in a unique data storage. These are very intrusive for health systems and their adoption results very complex. Second, proposals that make use of auxiliary data structures for referencing the health records, that remain stored in the information systems of health institutions and services. However, even when these proposals can be easily adopted and result less intrusive, they are not free of discussion. There are unresolved issues around them, such as the definition of who should keep this data structure alive and who should manage the access to it [14]. In addition, they also are controversial from the perspective of software engineering. Despite the above-mentioned issues were solved, none of them provide an easy and well-defined procedure for the development of software aware of the global health reality per patient that they offer. In other words, they do not offer an easily way of developing patient-centered healthcare software.

That is the reason why this paper offers a patient-centered solution that addresses the weaknesses of the existing solutions while maintaining the benefits already provided by them. To do this, and based on the unquestionable suitability that this technology has shown in previous proposals, blockchain is used. Specifically, this architecture makes use of the concept of blockchains' federation.

Thanks to this proposal, the *Personal Health Trajectory* is achieved without compromising its access by institutions and services, facilitating the development of *Patient Health Trajectory*-aware software and making the transition from actual institution-oriented systems to the new patient-oriented systems closer.

The rest of the document is structured as follows. Section II analyzes the literature for health data integration and interoperability. Section III introduces the concept of blockchains' federation for the health domain and describes the proposed solution. Section IV presents a reference implementation of the proposed solution and the procedure to develop *Patient Health Trajectory*-aware software using it. Section V details the validation performed to evaluate the reference implementation. Section VI brings a brief discussion by the analysis of the results obtained. Finally, in Section VII the conclusions of this work and some future lines of research are exposed.

II. Motivations and Related work

The integration of distributed health data is something on which researchers have been working for years. Over time, different proposals have arisen. On the one hand, some proposals advocate for the physical integration of the data into the same storage media. On the other hand, other proposals use additional structures that grant unified access to the data that remains distributively stored.

First, in the case of proposals physically integrating the data, proposals such as that of Spil et al. [16] or that of Kyazze et al. [9] can be found. Both propose the use of a client-server architecture to store and consult patient health data in a centralized manner. However, they are very intrusive for institutions, requiring them to migrate their data to a single repository.

To address the intrusiveness of this proposals, works like Zang et al. [10] proposes a client-server, multilayer architecture. In this architecture, a first data collection layer is used, followed by a data management layer. In this way, all data is collected and organized as needed. Thanks to this, integration is achieved without the need for institutions to migrate their data.

Different technologies can be used to create this kind of proposals, although the one considered as the most suitable is blockchain. Kassab et al. analyzed in their work [14] the suitability of blockchain to solve this problem of health data integration and compared it with other alternatives. From this analysis, the conclusion they obtain is that blockchain is a very promising technology, due to its distributed nature and its properties in data security and privacy [17].

Due to this, this technology has been employed by many proposals in the last few years. Since blockchain is not appropriate for the storage of heavy data, as some medical records can be, the proposals are not centered on using it to physically store records, but to store references to records. Proposals such as that of Roehrs et al. [18], that proposes the use of a blockchain per patient to store references to their different PHRs is one example. The proposal of Chen et al. [11] also makes use of blockchain to reference outside-stored records. However, in this case, the authors do explicitly that their proposal is not valid to monitor modifications and deletion of data. Some other proposals using blockchain to resolve this problem can be found in the commercial area, such as BurstIQ[1], SimplyVital[2] or MedicalChain[3].

Focusing more on the development of software consuming this integrated data, proposals such as [12] of Tanwar et al. arise. In this, the authors present a blockchain-based electronic healthcare record system on healthcare 4.0 applications for the development of applications using a self-defined SDK. Other researchers defining proposals that employ blockchains for data integration have focused on analyzing and improving the performance of these blockchains. Mayer et al. [13] propose the use of blockchains deployed on the fog instead of cloud-based blockchains, in order to improve the response time.

All these proposals achieve their objective and provide the integration of distributed health data without requiring institutions to migrate their data. However, they are not free of discussion [14]. Most of these proposals made use of a blockchain per patient that integrates all health data of a user. However, none of them provides an easy way of manage who owns this blockchain. Also, there is no way to ensure that this structure will be alive when health professionals want to interact with it.

Normally, most of the proposals suggest that patient holds this role since data belongs to them. If so, this implies that

[1]https://www.burstiq.com/
[2]https://www.f6s.com/simplyvitalhealth
[3]https://medicalchain.com/en/

institutions need that the patient permits them to use the global vision of their health with the problems that this can cause, specially in emergency situations.

In addition, and from a software engineering perspective, the usage of this type of proposal, where the location and access to the integrated data of a patient are not easy, the development of software that consumes this global vision is complex in most of the proposals.

These problems could be solved if proposals were created that offered alternative methods of access to this blockchain. For example, Ghost et al. [19] propose a decentralized gateway that allows interoperability between different private and public blockchains.

In this sense, proposals using various blockchains could be applied, in line with current Blockchain Interoperability (BI) proposals [20]. Proposals such as that of Wan et al. [21] define their own concept of Blockchain Federation, but based on integrating multi-blockchain functionalities with possible performance, security, acceptability, and other improvements.

Another option, contemplated by other proposals, is the usage of multiple blockchains, but in different levels of architecture. For example, proposals such as sidechains [22], that are based on the use of a blockchain that allows interacting with another series of blockchains underneath that are the ones that carry out the largest volume of transactions in the system. Other proposals, like Kan et al. [23], discuss the concept of multi-chain, where a router blockchain is used to make interoperable a series of lower-level blockchains. However, this proposal is not centered on reorganizing information from the different parties on the system across the blockchains, for duplications or inconsistencies removing in the patients' information. The authors of this paper have also previously worked on the definition of proposals [24] based on the use of various blockchains.

Thanks to the analysis of the literature, it has been noted that blockchain seems the most suitable option to achieve the interoperability of the distributed health data of a patient. However, it needs to be used in a more elaborated way than using only one blockchain per patient, since this solution creates some issues that can not be solved even if it is integrated as part of actual multi-blockchain approaches.

III. Proposal of solution: blockchains' federation and web services

This paper proposed a solution based on the use of the blockchains' federation concept and web services, for the unified access to distributed health data grouped by patients. For that, the concept of blockchains' federation applied to the health domain has been defined, and later it has been employed for the definition of an architecture. This architecture offers unified access to data, as well as promotes the development of health applications that use the *Personal Health Trajectory* of the patients. For this, it provides a connector whit which external health applications can connect to consume *Personal Health Trajectory* health data.

To facilitate the understanding of the proposal some blockchain concepts need to be explained. In a blockchain, data is organized as an immutable chain of blocks. These blocks are the ones in charge of storing the information so that the chain of blocks is the complete set of information: the blockchain. To access data, users must access that blockchain throughout a node. Therefore, multiple nodes for the same blockchain are defined. Each of them must have a complete copy of the blockchain. This copy is identical in all nodes since all of them are interconnected between them using a peer-to-peer network.

A. Blockchains' federation

The concept of blockchains' federation refers to the usage of multiple blockchains for managing data following a two-level infrastructure. In this way, as shown in Figure 1, in blockchains' federation several lower-level blockchains—patients' blockchains in the figure—can be interconnected using another blockchain—main blockchain–which is in charge of nesting them and providing access to all lower-level blockchains.

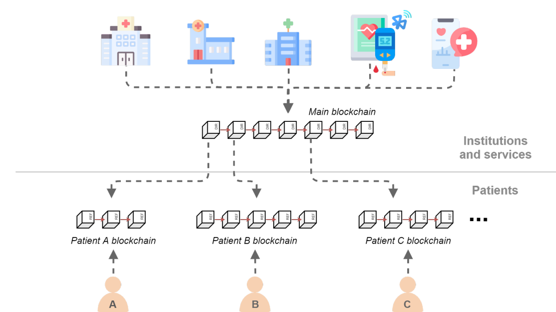

Fig. 1. Blockchains' federation applied to health domain

In blockchains' federation, the lower-level blockchains are in charge of saving the information in the system. Each of them is self-contained and can be considered a data structure independent of the federation. These blockchains are the ones in charge of storing the health data from patients. Specifically, each of these blockchains will belong to a patient, storing only her health data. This is one of the keys of our proposal since it allows to have all the *Personal Health Trajectory* of a patient organized in a single blockchain.

Having only one blockchain per patient in the whole system, it is ensured that there are not several partial realities of patient health. However, this implies that all institutions and services writing and reading information on the patient must have a way to locate such blockchain. To allow this, the usage of an additional structure storing where the blockchain of each patient is located is the easiest solution. This structure must contain the location of all patients' blockchains in the system and must be shared by all institutions and services employing the system.

For the implementation of this routing structure, blockchains' federation makes use of an additional blockchain:

the main blockchain. Each of its blocks stores the location of one of the patients' blockchains, as well as the information needed to identify the patient to which it belongs. Having each institution one node of the main blockchain, all of them can access data from all patients in the system. As well, all of them are going to be aware of any change/addition on patients' data or the location of their blockchains.

B. Architecture

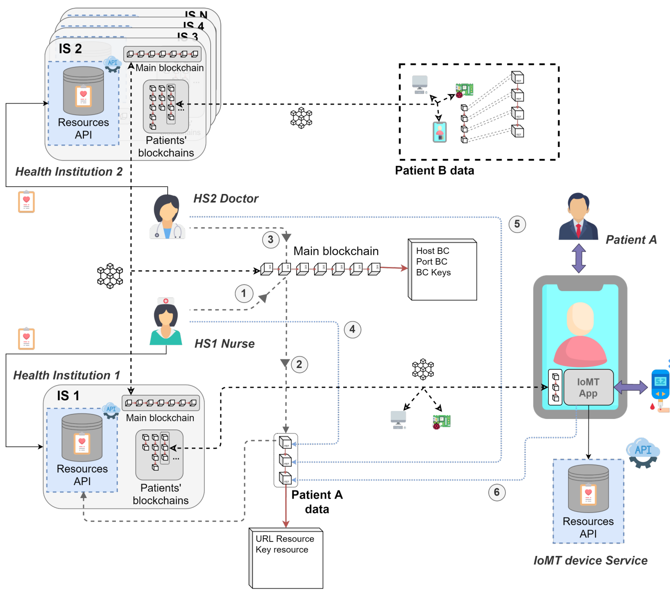

Fig. 2. Proposed architecture based on blockchains' federation and web services

Making use of the concept of blockchains' federation, an architecture that combines it with the usage of web services has been defined to solve the problem discussed throughout the paper. Figure 2 presents the components of the proposed architecture and their connections. The actors interacting with it are the health professionals of the health institutions involved in the system, the patients to which the data belongs, and their IoMT devices. The information systems providing the data integrated by this architecture are those of the health institutions and the IoMT devices.

The proposed architecture addresses the problem of distributed health data integration, solving the principal limitations of single blockchain proposals while maintaining their advantages. This is mainly achieved by the inclusion of the main blockchain and how it is employed to federate and organize the information in patients' blockchains. The following next paragraphs present how the proposed architecture achieves it, presenting first the redefinition that is done at the individual patient's level storage, and presenting later the inclusion of the main blockchains over it and how it contributes to the architecture.

One of the main components of the architecture is the patients' blockchains. This component is crucial since it is responsible for generating the *Personal Health Trajectory* for each patient. Therefore, each of these blockchains has the same responsibilities that the blockchain of the existent single blockchain's proposals. However, to solve the issues attributed to it in these proposals, some appreciations have been made in this architecture to the management of patients' blockchains. Because in the existent proposals the principal problem is that they do not define who was in charge of keeping a patient's blockchain alive and accessible, the proposed architecture defines a protocol to make it part of a well-known procedure by institutions and patients. In it, the main health institution to which a patient belongs at a given time is in charge of maintaining at least one node of the patient's blockchain. If the patient changes of main health institution, the new one must deploy a new node of the patient's blockchain. The old one can delete its node at that moment. Therefore, there will be always a node of the patient's blockchain, maintained by who is their main institution at each moment. In addition, the fact of using blockchain to maintain this patient's structure provides, among other advantages, that the patient can have a connected and updated copy of her data having a node of her blockchain in one of her devices at any time, empowering hers with greater control of her *Personal Health Trajectory* and allowing her to extract additional value from it.

As many of the blockchain-based proposals do, in our proposal the patients' blockchains do not directly store the health records. If records were stored in the blockchains directly, several problems arise, since blockchain is not able to store in their blocks data as heavy as some medical tests information can be. As well as other implications, such as that would limit the management of health records because data stored in a block of the blockchain cannot be modified or deleted later. So, as proposals that do not physically integrate the patients' health data, but make them interoperable through a mechanism of references, patients' blockchains in our proposal are employed to reference where the information is actually stored—instead of directly storing the patients' health information. Therefore, each block of these blockchains stores a reference to where the health information representing that block is stored. To facilitate this referral system, a Resources APIs is defined. Each healthcare institution and service, in its information system (labeled IS in the figure), deploys a Resources API and offers it as a web service. This Resources API stores health data generated at that institution or by IoMT devices using that service, for any patient in the system. However, the usage of this Resources API is not obligatory, and any other mechanism to store the data that allows referencing and remotely accessing it can be employed. This allows institutions and services to remain storing data in their actual storage support, without the need of migrating the data.

How these Resources APIs and patients' blockchains interact is that each time a new health record is added in a Resource API, a URL and key to access it is generated. This URL and key are stored in the blockchain of the patient to which the added health record belongs as a new block. This can be extended to store also information such as the operation performed on the health record referenced—storing a block not only when a record is added, but also when it is modified, deleted, or read—together with a hash computed with the content of the record each time a write operation is performed.

The second component that inherits this proposal of blockchains' federation is the main blockchain. Their functions are the same described in the presentation of the blockchains' federation concept. Therefore, each health institution must have a copy of this blockchain, shared by all of them, with which its health professionals interact. The initial institutions begin sharing the blockchain, where they must write the location of the blockchains of their patients when their administrators deploy them as a new block in the blockchain, together with some information for authorized the interaction with it, and other some information that allows identifying to which patient the block is referring for. Always must be referenced the node that the main institution must maintain for each of its patients. From that moment, each time a new institution is added to the system, the existent ones must accept their inclusion and this new will obtain a shared copy of the blockchain. After that, it will write the location of the blockchains of their patients also. If a patient changes from institution and therefore a new node is deployed to it, the new location is written in the main blockchain. Therefore, to locate the blockchain of a patient will be consulted always the location written in the last block referencing that patient. If an institution goes out of the system, it must delete its node of the main blockchain. To disable the access to their patient by the other institutions and services belonging to the system yet, the administrator can change the location of each patient blockchain node.

The IoMT services do not need to have a copy of the main blockchain, because, in this architecture proposed, they write the changes on their information about the patient using directly the copy she have of her blockchain in her own device. This implies that user must have a copy of her blockchain in her device if she want to include health information from her IoMT devices in her health trajectory. However, this simplifies notably the inclusion of information from any kind of IoMT devices with respect to needing that the services of all available IoMT devices brands join to all the systems using our proposal to share data among the different institutions that form a conglomerate. These services only need to offer a way to expose their information and modify their applications on smartphones to call a write operation in the patient's blockchain that user has indicated as hers. Due to their nature, smart devices do not need to read information from the *Personal Health Trajectory* of the patients.

Figure 2 shows the steps followed by the different actors when they interact with the *Personal Health Trajectory* of a patient. When a health professional wants to interact with a patient of her health systems, she consults the main blockchain node of their IS to locate where the patient's blockchain is deployed—steps 1 and 2—and, after locating it, write or read on it—step 4. In the same manner, when a health professional from another institution wants to interact with the same patient, even when the patient does not belong to the same institution, the procedure is similar. Instead of creating a new profile or blockchain for the patient in her information system—with the problems of duplication and inconsistencies already mentioned—she locates the patient existing blockchain through the main blockchain node of their institution's IS—steps 3 and 2—and operate with it writing or reading on it—step 5.

When the patient wants to add data from one of her smart IoMT devices, she does it by having a local copy of her blockchain in her smartphone and having installed the application of the smart device on it. The manufacturer of the devices must provide integration with our proposal, allowing her application to write data in a Resources API and allowing it to write a block referring it on the patient's blockchain—step 6.

In the case of being the patients who want to interact with their *Personal Health Trajectory* directly, the process is considerably simplified. Patients are not aware of the existence of the main blockchain, since they will interact directly with their blockchain, through the node maintained by their main institution or through the other node they can maintain on one of their devices.

To implement this architecture, some aspects should be taken into account. For example, the information stored in that system is private and should only be read and can be created by authorized entities. Only persons authorized by the patient should have access to her data. In the same manner, only persons authorized must have access to the main blockchain to locate patients' blockchains. For this reason, the usage of permissioned blockchains for the implementation of the components from the blockchains' federation is required.

IV. FedBlocks: A reference implementation of the proposal

A concrete implementation of the proposal of this paper is offered, serving as the reference implementation for it. This implementation provides the first functional tool based on our proposal available for being used by health systems. We called this tool as FedBlocks.

FedBlocks offers the different components discussed during the presentation of the architecture, ready to be included in the information systems of health systems; as well as some additional components for enhancing the developers experience developing healthcare software that employs our proposal as data source—*Personal Health Trajectory*-aware software.

For the implementation of blockchain components, Hyperledger Iroha[4] has been chosen. Iroha is one of the industrial implementations for permissioned blockchains that the Hyperledger project [25] offers. Its principal difference with the rest of the Hyperledger's implementations is that it includes a service—the Torii service—that allows remote working with the blockchains implemented with Iroha, without the need of

[4]https://github.com/hyperledger/iroha

a local copy or node. For this purpose, a series of APIs for the main programming languages are provided by Iroha, offering the operations to interact with the Torii service. From the different APIs available, the one for Python has been used in this proposal, to develop a connector and a REST API over it that allow the development of *Personal Health Trajectory*-aware applications and systems without the need of having local copies of the blockchains. This makes it easy to integrate the proposed solution into any kind of device, without the space or computational load limitations of having to host a blockchain node.

Therefore, the implementation done is highly dependent on the existence of this Torii service, allowing remote connection to nodes. Any other blockchain technology could be employed. For example, anyone not offering a similar remote connection service. However, this implies substantially changing the implementation done and the losing of advantages provided by Iroha.

All components of the architecture are deployed in the information systems of the institutions that integrate their patients' data. Additionally, the Resources APIs can be deployed also in IoMT devices' services integrating its data. A new Python connector and its REST API must be deployed along with the healthcare application that employs them for developing *Personal Health Trajectory*-aware software. The implementation of each of the components is discussed below and is available in public repositories—one[5] for information systems components and other[6] for connector.

V. VALIDATION

The reference implementation provided has been tested, in order to evaluate if it complies with their main function—generate *Personal Health Trajectory* for each of the patients, eliminating redundancies and the possibility of inconsistencies—as well as their performance—in order to measure delay introduced by the usage of the data structures needed for generate *Personal Health Trajectory* and to make it accessible for patients and health professionals.

To perform the validation of the proposal, an *Personal Health Trajectory*-aware application has been developed, using the reference implementation FedBlocks. This application allows doctors to interact with the data of the patients belonging to the system. Therefore, a doctor of any of the institutions sharing their patients' data can access to read and write records on them *Personal Health Trajectories*. In order to simplify the application, these records are encoded as a file of any type, containing the information of the different evaluations done to the patient. In a real environment, these records can be information of any type or even references to tuples of databases—if the application is extended to allow it. Global sharing of information such as allergies, blood group, or Covid-19 vaccination card of each citizen can be an example of the use of FedBlocks in healthcare. The implementation of the application is available in the Fedblocks' repository[7].

The evaluation has been divided into two phases. First, a conceptual evaluation and, second, a performance assessment. All tests performed and their values have been registered by the deployment of the FedBlocks architecture in the following environment:

- **Information Systems:** One EC2 General Purpose t2.xlarge instance from Amazon Web Services with Ubuntu 18.04 LTS, 4 virtual core at 2.3GHz, and 32GB of General Purpose SSD storage.
- **Doctor computer:** One laptop with Windows 10, 16GB of RAM, an Intel Core i7-8550U at 1.8GHz base frequency and 4.0GHz turbo frequency, and NVMe SSD storage.

A. Case study

To evaluate if the proposal is conceptually feasible, the case of MIAPe, a multidimensional healthcare assessment platform, is taken. MIAPe or *Multidimensional Integrated Assessment Platform for elderly* [26] is a platform developed by the authors of this paper. It is employed by health professionals and caregivers in different Portuguese healthcare and socio-geriatric centers to assess different aspects of their patients' health. Specifically, they evaluate seven different aspects, using the 12 forms available, as well as intelligent devices such as smartbands and smart scales. Additionally, a socio-demographic characterization of each patient is done, using another form that must be filled each time a new patient arrives for the system or when they have some update on their data.

At the time of writing, 50 different healthcare institutions maintain 5689 assessments and 1489 socio-demographic characterization cards from 1156 patients in a centralized manner in MIAPe.

B. Results

The performance of the proposal has been validated, in order to determine the delay it introduces when its components are employed over the actual information system of the institutions and services. The time needed to write a reference to a new record in the blockchain of a patient—going through the main blockchain to locate it—and to read all references to records of a patient—going through the main blockchain to locate it also—are measured.

Figure 3 shows these times when there is a configuration such as the one needed for the case study considered: 50 main blockchain's nodes, 1156 patients, 1 or 2 nodes per patient blockchain—all measurements have been replayed for both cases—, and from 1 to 500 records per patient. Read operation has been considered as the sum of reading the location of the patient blockchain in the main blockchain and reading all references to records in it. Write operation has been considered as the sum of reading the location of the patient blockchain in the main blockchain and writing a new block in the patient blockchain.

[5]https://bitbucket.org/spilab/is_components

[6]https://bitbucket.org/spilab/fedblocks_connector_api

[7]https://bitbucket.org/spilab/doctor_app

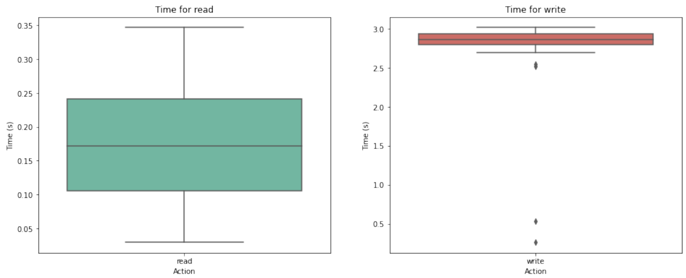

Fig. 3. Times per main actions

As can be seen in this figure, the reading operation is of the order of a few tenths of a second (0.16 seconds), so it can be considered that it is not an impediment to the user experience. However, the write operation is more costly. In this case, adding a record for a patient takes about 2.87 seconds. This increase in time is caused by the need of generating a block in that patient's actor blockchain and should be balanced against the reduced duplication and inconsistencies provided by FedBlocks.

In order to ensure that, Figure 4 shows the average time consumed by each of the low-level operations involving the previous one, as well as the operations needed for writing and reading on the Resources APIs. However, we consider that these last operations do not need more discussion, since they are highly dependent on the size of the file stored as a record—even the institutions and services can use their actual storage systems instead of the Resources APIs.

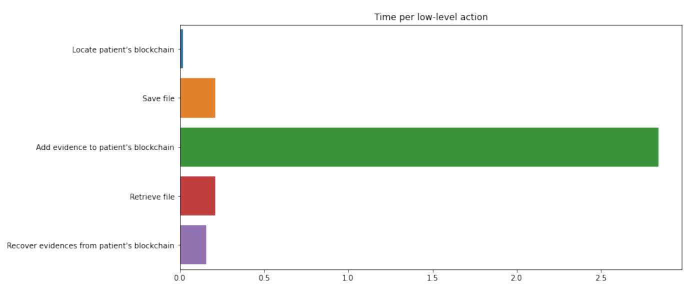

Fig. 4. Times per low-level actions

VI. Discussion

Having validated the proposal and verified the results obtained, this section aims to determine whether the proposal makes a really useful contribution to the current state of the art in this field of research. The results obtained during validation are those expected. As can be seen in the previous section, the delay that the proposal introduces with respect to the direct interaction with storage media could be an expected problem. However, thanks to the validation, we have determined that it is not a real problem since delay can be despised in favor of the benefits provided by the proposal. Even taking into account that the case study in which it was tested is a small case study. In any public health system, there are more patients than there are in the case study of this paper, with a larger number of EHRs and even heavier.

The first thing to make clear is what is the main contribution of this proposal to the creation of patient-centered healthcare systems and the integration of distributed healthcare data. In this sense, the use of a blockchain to store the references of all the healthcare data of a patient is not. This is already done by other proposals, where the suitability of this technology has already been sufficiently demonstrated. The real and main contribution of this proposal is the use of the blockchains federation to facilitate access to integrated patient information by institutions and to keep alive the structure that integrates the data of each patient, maintaining the advantages already offered by other current proposals.

Other major benefits of the proposal is the enabling pf *Personal Health Trajectory*-aware software. In this way, it will be possible to develop healthcare systems working with the *Personal Health Trajectory* directly much faster, facilitating the transition from the current systems to these.

Another important point to make in this discussion is the need for sharing patient data across health systems. Since they are the ones who must accept that this is happening, it is necessary to make them see the benefit for them, for society in general, and that this is safe since nothing will be shared that they do not accept and that they will not be able to see that it is being shared.

Before concluding the discussion, it is also important to note that with the proposal made in this paper, the applicability of blockchain to move from actual institution-centered health systems to a truly patient-centered system has been reaffirmed. First, because blockchain promotes decentralization, exchange, and openness while ensuring data traceability and security. Secondly, the various advantages referred to in the proposal are made possible thanks to the blockchain. In general, the fact that architecture preserves the *Personal Health Trajectory* for the patient. So, with all this in mind, the importance of the blockchain to this proposal is obvious.

Several efforts have been made to provide a structure as less intrusive as possible for institutions and services. So elements such as Resources APIs or connectors were used. They are also allowed to maintain their actual storage system, as long as the stored information can be referenced from the blockchain.

VII. Conclusions and Future Work

This paper proposed new way of develop patient-centered health systems through the *Personal Health Trajectory* of patients. For this, it makes a use of a new concept defined over blockchain, making interoperable data that remains stored in different, distributed places. This reduce intrusiveness of the proposal and making easier their adoption by actual health systems.

Additionally, the proposal described in this paper put special interest in the simplification of the development of software aware of this *Personal Health Trajectory*. So, a connector ready to be included in any software application is provided.

In this way, the achieved *Personal Health Trajectory* not only serves as a resource to manual analysis, but it information can be employed to develop any kind of application with them.

Despite all this, the proposal in this paper may be controversial, given that its use implies that healthcare institutions and services must share their patients' data with other institutions and services. If data are not shared, integration cannot be achieved. This can also be misinterpreted as a privacy issue. However, it should not be forgotten that the proposal seeks a benefit for patients. Therefore, as long as data protection regulations are complied with and the patient's approval is obtained, the sharing of her data will be done in benefit to her. Likewise, if a patient does not wish to share her data, it will be sufficient with not having a patient blockchain to generate her *Personal Health Trajectory*.

As future work on the proposal, its deployment in production is one of the tasks that the authors of the article seek to complete. Also pending is the inclusion of tools to extract the content of the different records—each in a different format and with a different data model—to facilitate the use of this data in automatic tools.

Acknowledgment

This work is part of the Grants PID2021-1240454OB-C31 and FPU19/03965 funded by MCIN/AEI /10.13039/50100011033, by "ERDF A way of making Europe" and by Cáceres Provincial Council (AV-6). It is also supported by the QSALUD project (EXP 00135977 / MIG-20201059) in the lines of action of the Center for the Development of Industrial wTechnology (CDTI); and by the proyect 0786_CAP4ie_4_P (Interreg V-A España-Portugal 2021-2027).

References

[1] J. Rojo, E. Moguel, C. Fonseca, M. Lopes, J. Garcia-Alonso, and J. Hernandez, "Time series forecasting to predict the evolution of the functional profile of the elderly persons," in *International Workshop on Gerontechnology*. Springer, 2020, pp. 11–22.

[2] D. Kalra, "Electronic health record standards," 2006.

[3] A. Gatouillat, Y. Badr, B. Massot, and E. Sejdic, "Internet of Medical Things: A Review of Recent Contributions Dealing with Cyber-Physical Systems in Medicine," *IEEE Internet of Things Journal*, vol. 5, no. 5, pp. 3810–3822, oct 2018.

[4] J. Rojo, D. Flores-Martin, J. Garcia-Alonso, J. M. Murillo, and J. Berrocal, "Automating the interactions among iot devices using neural networks," in *2020 IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom Workshops)*. IEEE, 2020, pp. 1–6.

[5] A. Roehrs, C. André Da Costa, R. Da, R. Righi, Kleinner, and S. Farias De Oliveira, "Personal Health Records: A Systematic Literature Review," *Journal of Medical Internet Research*, vol. 19, no. 1, p. e13, 2017. [Online]. Available: http://www.jmir.org/2017/1/e13/

[6] D. Flores-Martin, J. Rojo, E. Moguel, J. Berrocal, and J. M. Murillo, "Smart nursing homes: Self-management architecture based on iot and machine learning for rural areas," *Wireless Communications and Mobile Computing*, vol. 2021, 2021.

[7] N. Mäkitalo, D. Flores-Martin, J. Berrocal, J. García-Alonso, P. Ihantola, A. Ometov, J. M. Murillo, and T. Mikkonen, "The internet of bodies needs a human data model," *IEEE Internet Computing*, vol. 24, no. 5, pp. 28–37, 2020.

[8] J. Rojo, J. Hernandez, and J. M. Murillo, "A personal health trajectory api: Addressing problems in health institution-oriented systems," in *Web Engineering*, M. Bielikova, T. Mikkonen, and C. Pautasso, Eds. Cham: Springer International Publishing, 2020, pp. 519–524.

[9] M. Kyazze, J. Wesson, and K. Naude, "The design and implementation of a ubiquitous personal health record system for south africa," *Studies in health technology and informatics*, vol. 206, p. 29, 2014.

[10] Y. Zhang, M. Qiu, C.-W. Tsai, M. Hassan, and A. Alamri, "Health-cps: Healthcare cyber-physical system assisted by cloud and big data," *IEEE Systems Journal*, vol. 11, pp. 1–8, 08 2015.

[11] L. Chen, W. K. Lee, C. C. Chang, K. K. R. Choo, and N. Zhang, "Blockchain based searchable encryption for electronic health record sharing," *Future Generation Computer Systems*, vol. 95, pp. 420–429, jun 2019.

[12] S. Tanwar, K. Parekh, and R. Evans, "Blockchain-based electronic healthcare record system for healthcare 4.0 applications," *Journal of Information Security and Applications*, vol. 50, p. 102407, feb 2020. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S2214212619306155

[13] A. H. Mayer, V. F. Rodrigues, C. A. da Costa, R. da Rosa Righi, A. Roehrs, and R. S. Antunes, "Fogchain: a fog computing architecture integrating blockchain and internet of things for personal health records," *IEEE Access*, vol. 9, pp. 122 723–122 737, 2021.

[14] M. Kassab, J. Defranco, T. Malas, V. V. Graciano Neto, and G. Destefanis, "Blockchain: A panacea for electronic health records?" in *Proceedings - 2019 IEEE/ACM 1st International Workshop on Software Engineering for Healthcare, SEH 2019*. Institute of Electrical and Electronics Engineers Inc., may 2019, pp. 21–24.

[15] A. Dubovitskaya, P. Novotny, S. Thiebes, A. Sunyaev, M. Schumacher, Z. Xu, and F. Wang, "Intelligent health care data management using blockchain: current limitation and future research agenda," in *Heterogeneous Data Management, Polystores, and Analytics for Healthcare*, 2019, pp. 277–288.

[16] T. Spil and R. Klein, "Personal health records success; why google health failed and what does that mean for Microsoft HealthVault?" in *Proceedings of the Annual Hawaii International Conference on System Sciences*. IEEE Computer Society, 2014, pp. 2818–2827.

[17] J. Wan, C. Han, X. Yu, Y. Ren, and R. S. Sherratt, "Distributed secure storage scheme based on sharding blockchain," *Computers, Materials & Continua*, vol. 70, no. 3, pp. 4485–4502, 2022. [Online]. Available: http://www.techscience.com/cmc/v70n3/44975

[18] A. Roehrs, C. A. da Costa, and R. da Rosa Righi, "OmniPHR: A distributed architecture model to integrate personal health records," *Journal of Biomedical Informatics*, vol. 71, pp. 70–81, jul 2017.

[19] B. C. Ghosh, T. Bhartia, S. K. Addya, and S. Chakraborty, "Leveraging public-private blockchain interoperability for closed consortium interfacing," *arXiv preprint arXiv:2104.09801*, 2021.

[20] A. Lohachab, S. Garg, B. Kang, M. B. Amin, J. Lee, S. Chen, and X. Xu, "Towards Interconnected Blockchains: A Comprehensive Review of the Role of Interoperability among Disparate Blockchains," *ACM Computing Surveys*, vol. 54, no. 7, sep 2022.

[21] Z. Wan, M. Cai, X. Hua, J. Yang, and X. Lin, "Blockchain federation enabled trustable internet of things," in *Services – SERVICES 2020*, J. E. Ferreira, B. Palanisamy, K. Ye, S. Kantamneni, and L.-J. Zhang, Eds. Cham: Springer International Publishing, 2020, pp. 61–76.

[22] A. Singh, K. Click, R. M. Parizi, Q. Zhang, A. Dehghantanha, and K.-K. R. Choo, "Sidechain technologies in blockchain networks: An examination and state-of-the-art review," *Journal of Network and Computer Applications*, vol. 149, p. 102471, 2020.

[23] L. Kan, Y. Wei, A. Hafiz Muhammad, W. Siyuan, L. C. Gao, and H. Kai, "A multiple blockchains architecture on inter-blockchain communication," in *2018 IEEE International Conference on Software Quality, Reliability and Security Companion (QRS-C)*, 2018, pp. 139–145.

[24] J. Rojo, J. Hernandez, J. M. Murillo, and J. Garcia-Alonso, "Blockchainsâ€™ federation for integrating distributed health data using a patient-centered approach," in *2021 IEEE/ACM 3rd International Workshop on Software Engineering for Healthcare (SEH)*, vol. 1. Los Alamitos, CA, USA: IEEE Computer Society, jun 2021, pp. 52–59. [Online]. Available: https://doi.ieeecomputersociety.org/10.1109/SEH52539.2021.00016

[25] V. Dhillon, D. Metcalf, and M. Hooper, *The Hyperledger Project*. Berkeley, CA: Apress, 2017, pp. 139–149.

[26] E. Moguel, J. Berrocal, J. M. Murillo, J. García-Alonso, D. Mendes, C. Fonseca, and M. Lopes, "Enriched elderly virtual profiles by means of a multidimensional integrated assessment platform," in *Procedia Computer Science*, vol. 138. Elsevier B.V., jan 2018, pp. 56–63.