Cooperative Algorithm to Improve Temperature Control in Recovery Unit of Healthcare Facilities

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Abstract. Healthcare facilities spend a lot of resources on taking care of patients while they recover from their illnesses. IoT (Internet of Things) devices are used to monitor and control the environment of healthcare facilities. According to Spanish standards of hygiene and safety in hospitals: the temperature must be between 18 ° and 24 °C and relative humidity of 60%. In this paper, we present a cooperative control algorithm to increase data quality and false data detection via edge computing in healthcare facilities. Furthermore, it is demonstrated that blockchain can be used to store data in an immutable and secure way. In this work we present a new model for the efficient control and monitoring of indoor temperature in healthcare facilities, reducing energy consumption and storing data in a secure and immutable way via blockchain.

Keywords: IoT · Algorithm design · Game theory · e-health · Blockchain · Cooperative control

1 Introduction

In the last few years, the term blockchain has been very frequently used among the scientific community. Gartner proposed in July 2016 that blockchain was a distributed database. First described by Nakamoto in 2008, he developed the concept of Bitcoin, an encryption-based virtual currency. Today, Bitcoin is the most advanced application of blockchain and the most advanced technological concept in academia. However, blockchain has many more applications in other fields and industries. Since Bitcoin's blockchain only serves to store cryptocurrency transactions, other blockchain systems have been developed (e.g., Ethereum) for making smart contracts and storing a wide variety of data. Ethereum is a decentralized platform that runs smart contracts: applications that run exactly as programmed, without any possibility of downtime, censorship, fraud or third-party interference. This enables developers to store registries of data, move funds in accordance with instructions given long in the past (like a will or a future

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contract) and many other things that have not been invented yet, all without a middleman or counterparty risk. Ethereum makes it possible to establish smart contracts between several parties. Several actions are involved in the process of making smart contracts in the blockchain. To build a block with the data collected by the smart nodes, the smart contract runs. Once the block is validated by the miners, it can be introduced into the blockchain. Furthermore, since network consensus is always necessary, altering records becomes very difficult and expensive. This prevents individuals or groups from changing a blockchain record with the effort of trying to make false data look precise and authentic [5].

One of the problems detected by the authors in monitoring and controlling the environment in which patients recover is that the temperature in the rooms is not constant. There are several reasons for this, one of the main causes is that the patients' family members may change the temperature of their thermostats, open the windows of their rooms, etc. As a consequence of temperature fluctuations, patients have more difficulties in restoring their health. Furthermore, to ensure that patients are at the temperatures that are recommended by national regulations, many resources are wasted on heating and cooling. This results in low-quality healthcare as professionals are limited by the control systems available to them. Therefore, we consider it necessary to develop a new e-health model that will have all the functionalities required for monitoring and controlling temperature in healthcare facilities. There have been attempts to use multi-agent systems to optimize and improve the e-health system [2] however, the implementation of a WSN does not eliminate the key problems of centralized systems [6].

In this paper, a new temperature control system is proposed for use in the field of e-Health. This new system has an architecture with an edge computing layer in which data is transformed by applying an algorithm to improve data quality and false data detection. In this way, it is possible to improve efficiency in monitoring healthcare facilities. In the case study presented in this paper, IoT devices monitored the temperature of a healthcare facility. The cooperative algorithm that is executed in edge computing layer increases data quality by using game theory to reach temperature consensuses between IoT e-health devices and auto-correcting the inaccurate temperatures. Thus, the use of energy to heat or cold healthcare facilities can be optimized, offering a better-quality service to the patients. On the other hand, blockchain technology is used in this system to store temperatures. Thus, only authorized staff have access to this data. This paper is organized as follows: Sect. 2 reviews the literature related to blockchain. Section 3 proposes the architecture and the cooperative algorithm. Section 6 draws conclusions from the conducted research.

2 Related Work

Many researchers have done paramount studies on networking architectures. In the field of medicine the literature features examples of architectures for IoT in various fields such as military health services on the battlefield [22], ambient assisted living applications [17], patient health monitoring system [12] and hospitalized patient monitoring [7]. Other researchers use the support of IoT architectures to present their algorithms for e-health [9]. Some of the latest work in this field is the use of algorithms to detect Alzheimer's disease [27], algorithms for monitoring and alerting system [16], regular monitoring of arthritis disease [20] and early detection of heart diseases [15,31]. In this line our research focuses on presenting an algorithm to monitor and control temperature in patient recovery environments. To achieve this, we present an IoT architecture for smart Hospital in which the proposed algorithm can be used. Many researchers assume that "WSNs are subsets of IoT". WSNs are used to control and monitor a wide range of things [11,32]. Some works achieve good results in fields such as energy efficiency using WSNs [3], control of operations [8], optimal routing in WSNs [26,33], and some other applications such as social good [21]. Sensor networks can also be used with other technologies such as multi-agent systems to manage data [26], for data mining [23], multi-agent localization and WSN. These algorithms are also being used for data mining [1,34]. Moreover, WSNs and GT are the areas that are currently undergoing intense study, [10] is focused on finding innovative solutions to the challenges presented by next-generation WSNs. Since GT is an ideal tool for designing efficient and robust distributed algorithms, its use in the design and analysis of WSN information is attracting increased attention [19,35]. This survey looks at how GT is currently being used in WSNs. In [25,36] the authors make a general classification of the different uses of GT in WSNs; they are classified into the following groups: network management, communication, network security and applications. Our proposal can be included in the applications category, within the data collection subgroup.

Existing works provide diverse frameworks for blockchain and IoT. Moreover, applications that merge both technologies are being developed. One of the earliest development was an application that authenticates and increases the reliability of WSNs using blockchain [4,37] [18,38]. Other applications also combine the Internet of Things and the global commerce [13,39]. Regarding the blockchain-based architectures, Q. Xia et al. [28] provide a framework for the exchange of health data based on a blockchain that addresses the access control challenges associated with sensitive data stored in the cloud. The system is based on a blockchain with permissions that allow access only to invited and therefore verified users. Yue et al. [29] present an architecture based on 3 layers: data usage layer, data management layer and data storage layer. This paper discusses the use of a private blockchain that acts as a cloud. Kuo et al. [14] make an in-depth revision of the latest biomedical/sanitary applications of blockchain technologies. The authors discuss the potential changes that these applications and architectures need and suggest solutions using the blockchain technology in the biomedical/sanitary field. In contrast to this work focused on the exchange of health data, [24,40] and [30] focus on other problems. Shae et al. [24] propose a blockchain-based architecture for clinical trials and precision medicine. Zhao et al. [30] use a WSN to design a lightweight backup and efficient recovery scheme for healthcare systems. This is a pioneering work in blockchain key management, while its performance is heavily influenced by the state of the hardware and environment.

The methods presented in the reviewed literature overcome different challenges concerning e-health. IoT architectures and blockchain-based architectures are presented in response to several issues detected by researchers. However, we observed a gap in the literature review since there are no algorithms that could automatically validate the temperature collected by a heterogeneous WSN. In our work, coalitions of neighbours are created by using clustering techniques. This distributed and self-organized (overall temperature equilibrium arises from local game interactions between sensors of an initially disordered temperature system) game is designed to provide reliability and robustness to the data collected by a WSN. It identifies defective sensors gathering inaccurate measurements and detects areas with similar temperatures. This article tackles the problem of reliability of WSN data from the point of view of game theory and probability, which is a novel approach in this field.

3 Proposed Architecture

The main goal of this work is to present a cooperative control algorithm that improves data quality of the temperature collected by the smart WSN nodes. To achieve our goal, we propose an architecture that allows to monitor and control the temperature of healthcare facilities. Through the literature review, we present a 3-layer architecture: data collection layer, data management layer and data storage and security layer.

3.1 Proposed System Architecture

This architecture has 3 layers: (1) Data collection layer. Sensors collect data from the environment or object under measurement and turn it into useful data. Data is at the core of an IoT architecture, and we have to decide between the immediacy and depth of knowledge when processing these data. The more immediate the need for information, the closer to the end devices your processing needs to be. The data from the sensors is started in analog form. The DAS connects to the WSN, adds inputs and carries out the transformation from analog to digital. The Internet gateway receives the digitized data and routes it to the data management layer for further processing. Here, temperature sensors monitor the temperature of healthcare facilities. (2) Data management layer. Once data has been digitized it is ready to enter the data management layer. However, data may require processing before entering the storage layer. This is where edge computing systems come into play, they perform more analyses. Usually, devices that are in the edge computing system sit in the facility or location where the sensors reside closer to the sensors (i.e., Smart controller). Digitized data is sent to the smart controllers. Then, the Raspberry Pi first runs a cooperative control algorithm to improve data quality and false data detection. Once data is transformed by the cooperative control algorithm, Raspberry Pi sends the data to the sidechain (this sidechain is Rinkeby, a fork of Ethereum) that builds the block with the data sent to it by the IoT nodes. Once the block is built in the sidechain, the Raspberry Pi runs a smart contract in the Ethereum blockchain (i.e., main chain) to validate the sidechain of a new block. If the block is validated, the Raspberry Pi sends the block to the miners' network for storage in the blockchain. (3) Storage and security layer. In blockchain network, there are two important entities: Miners and verifiers. Miners refer to the nodes who produce new blocks for the blockchain. Different application scenarios may define different nodes as the miners. New blocks are accepted only after validation by the verifiers, which are responsible for verifying the new blocks' authenticity. Processes of generation, verification and inclusion of new blocks in the blockchain are called mining. To ensure the safety and reliability of mining processes, the consensus mechanism is critical in the blockchain network. In this work, transactions denote the temperature of the healthcare facilities records in the system. In relation to our work, Ethereum blockchain is introduced in the e-Health system to store and manage the temperature, which helps to improve the recovery time.

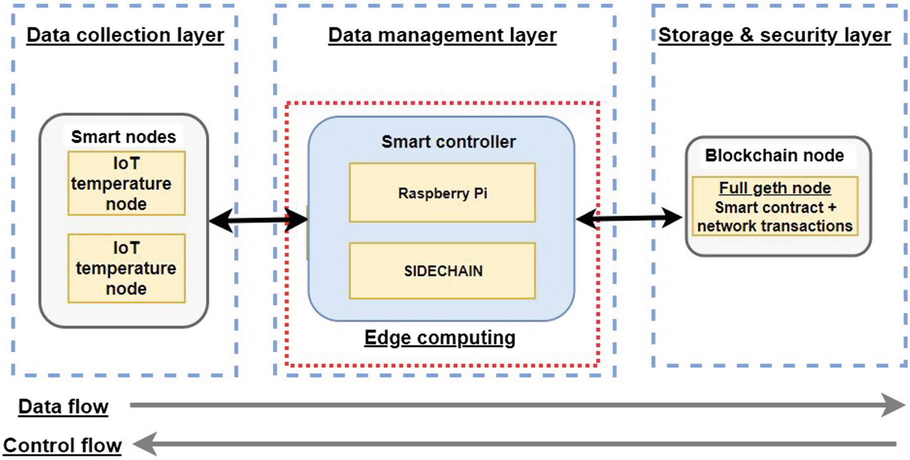

Fig. 1. High-level system architecture design diagram. Central to our research is an Ethereum blockchain, which provides a mechanism to execute logic and manage node interactions via smart contracts. Nodes share a blockchain database and communicate over the blockchain.

4 Cooperative Control Algorithm

The cooperative control algorithm requires the data to be in a matrix. Therefore, the first transformation that data has is to place them in an ordered mesh from point (1,1) to point (n,n) so that each of these points matches the position of the smart nodes. From the mesh it is easy to create a matrix in which the cooperative control algorithm is applied. Without loss of generality, if we have a mesh with n sensors ordered from (1,1) to (n,n), matrix shown in Eq. 1 is created.

$$T_{n,n} = \begin{pmatrix} t_{s_{1,1}} & \dots & t_{s_{1,n}} \\ \vdots & \ddots & \vdots \\ t_{s_{n,1}} & \dots & t_{s_{n,n}} \end{pmatrix} \tag{1}$$

4.1 Mathematical Description of the Algorithm

Let $n \geq 2$ denote the number of players in the game, numbered from 1 to n, and let N = {1, 2,...,n} denote the set of players. A coalition, S, is defined to be a subset of N, $S \subseteq N$, and the set of all coalitions is denoted by $\mathbb{S}$. A cooperative game in N is a function u (characteristic feature of the game) that assigns to each coalition $S_i \subseteq \mathbb{S}$ a real number $u(S_i)$. In addition one has the condition $u(\emptyset) = 0$. In our case, the game will be non-negative (the values of the characteristic function are always positive), monotonous (if more players are added to the coalition the value of the expected characteristic function does not change), simple and 0-normalized (players are obliged to cooperate with each other since individually they will obtain zero benefit).

In our case, the set of players is the set of ordered sensors S and the characteristic function u is defined as:

$$u : 2^n \longrightarrow \{0, 1\} \tag{2}$$

such that, for each coalition of sensors, u = 1 or 0 if that particular coalition can vote or not respectively (see Eq. (2, 3)).

$$\mathbb{S} \ni S_i \longrightarrow u(S_i) = \{0, 1\} \in \mathbb{R} \tag{3}$$

where $\mathbb{R}$ are the Real numbers.

4.2 Cooperative Sensor Coalitions

The possible coalitions that the sensors will form, will be limited by their position, that is, the coalitions can only be formed by neighbouring sensors. Let's consider the matrix of the sensors and a pair of sensors $s_{i,j}$ and $s_{k,m}$ will be in the same neighbourhood if and only if:

$$\parallel (i-k)^2 - (j-m)^2 \parallel \leq 1 \tag{4}$$

that is, if each sensor to which the game is applied, is the center of a Von Neumann neighbourhood, its neighbours are those lying within a Manhattan distance (in the matrix) equal to one. In addition, the following conditions have to be fulfilled by the allowed coalitions:

1. Coalition sensors have to be in the same neighborhood as defined in Eq. 4.
2. Coalitions cannot be formed by a single sensor.

4.3 A Characteristic Function to Find *cooperative* temperatures.

In the proposed game, we want the neighbourhood coalitions to democratically decide the temperature of the main sensor. To do this, they will form coalitions that will decide on the final temperature of the sensor, which will be determined by whether they can vote or not in the process. From the characteristic function defined in Eq. (2), if the value is 1(0), the coalition can vote (not vote) respectively. s_i is the main sensor with its associated temperature t_{s_i}, the characteristic function is built in the following way:

1. First, the average temperature of all the sensors is calculated:

$$T^k_{s_i} = \frac{1}{V}\sum_i^V t_{s_i} \tag{5}$$

   here $T^1_{s_i}$ represents the average temperature of the sensors' neighbourhood s_i (including it) in the first iteration of the game and V is the number of neighbours in the coalition.
2. The next step is to compute an absolute value for the temperature difference between the temperatures of each sensor and the average temperature:

$$\overline{T}^k_{s_i} = \left(\frac{1}{V}\sum_i^V \mid t_{s_i} - T^k_{s_i} \mid^2\right)^{\frac{1}{2}} \tag{6}$$

3. Using the differences in temperature values with regards to the average temperature $\overline{T}^k_{s_i}$ (see Eq. (6)) a confidence interval is created and defined as follows:

$$I^k_{s_i} = \left(T^k_{s_i} \pm t_{(V-1,\frac{\alpha}{2})}\frac{\overline{T}^k_{s_i}}{\sqrt{V}}\right) \tag{7}$$

   in Eq. (7) we use the Student's-t distribution with an error of 1%.
4. In this step we use a hypothesis test. If the temperature of the sensor lies in the interval $I^k_{s_i}$, it belongs to the voting coalition, otherwise, it is not in the voting coalition:

$$u^k(s_1,\ldots,s_n) = \begin{cases} 1 \text{ if } t_{s_i} \in I^k_{s_i} \\ 0 \text{ if } t_{s_i} \notin I^k_{s_i} \end{cases} \tag{8}$$

5. The characteristic function will repeat this process iteratively (k is the number of the iteration) until all the sensors in that iteration belong to the voting coalition. In each iteration k, the following payoff vector of the coalition S_j (with $1 \le j \le n$ where n is the number of sensors in the coalition) in the step k ($PV(S^k_j)$) is available:

$$PV(S^k_j) = (u^k(s_1),\ldots,u^k(s_n)) \text{ where } \sum_i^n u^k(s_i) \le n \tag{9}$$

The stop condition of the game iterations is $PV(S_j^k) = PV(S_j^{k+1})$ the process end. That is, let $PV(S_j^k) = (u^k(s_1), \ldots, u^k(s_n))$ and let $PV(S_j^{k+1}) = (u^{k+1}(s_1), \ldots, u^{k+1}(s_n))$. The iteration process ends when both payoff vectors contain the same elements. This process is shown in the following equation:

$$\begin{cases} u^k(s_1) = u^{k+1}(s_1) \\ \vdots \\ u^k(s_n) = u^{k+1}(s_n) \end{cases} \tag{10}$$

Solution Concept of the Cooperative Game. Once the characteristic function has been applied to all sensors involved in this step of the game a payoff vector in the step k is available (see Eq. 9). Since the proposed game is a cooperative game, the solution concept is a coalition of players that we have called game equilibrium (GE). The GE of the proposed game is defined as the minimal coalition with more than half of the votes cast. Let n be the number of players involved in this step of the game. Winning coalition must satisfy the following conditions:

1. Sum of the elements of the coalition PV must be higher than half plus 1 of the votes cast:
$$\sum_i^n u^k(s_i) \geq \frac{n}{2} + 1 \tag{11}$$
2. The coalition is maximal (i.e., coalition with the greatest number of elements, different from 0, in its payoff vector $PV(S_j^k)$).

Therefore, the solution to the proposed game is the coalition that verifies both conditions from among all possible coalitions that are formed at each step k of the game.

4.4 Temperatures of the Winning Coalition

Once the characteristic function decides which is the winning coalition, it is possible to calculate the temperature of the main sensor. Let $\{s_1, \ldots, s_j\}$ be the winning coalition's sensors and $\{t_{s_1}, \ldots, t_{s_j}\}$ be their associated temperature.

The temperature that the game has voted to be the main sensor's temperature (MST) is calculated as follows:

$$MST = \max_{j \in |S_{winner}|} \{j * t_{s_i}\}_{s_i \in S_{winner}} \tag{12}$$

where $|\mathbb{S}|$ is the number of elements in the winning coalition. Therefore, the MST will be the maximum temperature that has the highest relative frequency. In case of a draw, it is resolved by the Lagrange criterion.

Diffuse Convergence. In each game iteration, there is a matrix with temperature (see Eq. 1). Hence we define a sequence of arrays $\{M_n\}_{n\in\mathbb{N}}$ where the M_i element corresponds to the temperature matrix in step i of the game. Therefore, it can be said that the sequence of matrices is convergent if:

$$\forall\epsilon > 0, \text{ there is } N \in \mathbb{N} \text{ such that } |M_{i-1} - M_i| \leq \epsilon \ \forall i \in \mathbb{N}. \tag{13}$$

That is, if the element $m^{i-1}_{n,m} \in M_{i-1}$ and the element $m^{i}_{n,m} \in M_i$ are set and the convergence criterion is applied, we have:

$$\begin{aligned} \forall\epsilon_{n,m} > 0 \text{ there is } N \in \mathbb{N} \text{ such that } |m^{i-1}_{n,m} - m^{i}_{n,m}| \leq \epsilon_{n,m} \\ \forall i \in \mathbb{N}\ ,\ \forall i \geq N \text{ and } m^{i-1}_{n,m} \in M_{i-1}, m^{i}_{n,m} \in M_i \end{aligned} \tag{14}$$

Therefore, by applying the criterion of convergence in Eq. (14) to all the elements, a new matrix is obtained with the temperature differences between the temperatures obtained in previous and in the next step of the game.

$$\begin{pmatrix} |m^{i-1}_{1,1} - m^{i}_{1,1}| & \dots & |m^{i-1}_{1,m} - m^{i}_{1,m}| \\ \vdots & \ddots & \vdots \\ |m^{i-1}_{n,1} - m^{i}_{n,1}| & \dots & |m^{i-1}_{n,m} - m^{i}_{n,m}| \end{pmatrix} \tag{15}$$

For the succession of matrices to be convergent, each of the sequences of elements that are formed with the $|m^{i-1}_{n,m} - m^{i}_{n,m}|$ must be less than the fixed $\epsilon > 0$. In this work, it is established that $\epsilon = 0.01$. The game reach the equilibrium if at least 80% of the elements of the matrix are convergent.

5 Empirical Results of the Case Study

In this case study the temperature of a recovery unit of a hospital in Salamanca (Spain) was collected. The IoT nodes collect data from the rooms and corridors. Then, the cooperative algorithm is used to increase the quality of the collected data and false data detection. In this way the hospital can monitor the temperature of the environment more effectively. Finally, data that has been transformed is stored in the blockchain. Once the mesh is made with the position of the IoT temperature nodes, the temperature is collected and stored in a matrix. In this case study, the cooperative algorithm is executed in the edge computing layer, transforms data before it reaches blockchain. The type of sensor used (in the IoT temperature nodes) is a combination of the ESP8266 microcontroller in its commercial version "ESP-01" and a DHT11 temperature and humidity sensor (Fig. 1). Their combination allows for greater flexibility when collecting data and adaptability to the case study, since the DHT11 sensor is designed for indoor environments (has an operating range of between 0 °C and 50 °C) according to its datasheet. The microcontroller collects data from this sensor through a onewire protocol and communicates it to the environment via WiFi using HTTP standards and GET/POST requests. The device is programmed using the ESP-IDF programming environment provided by the manufacturer of the microcontroller.

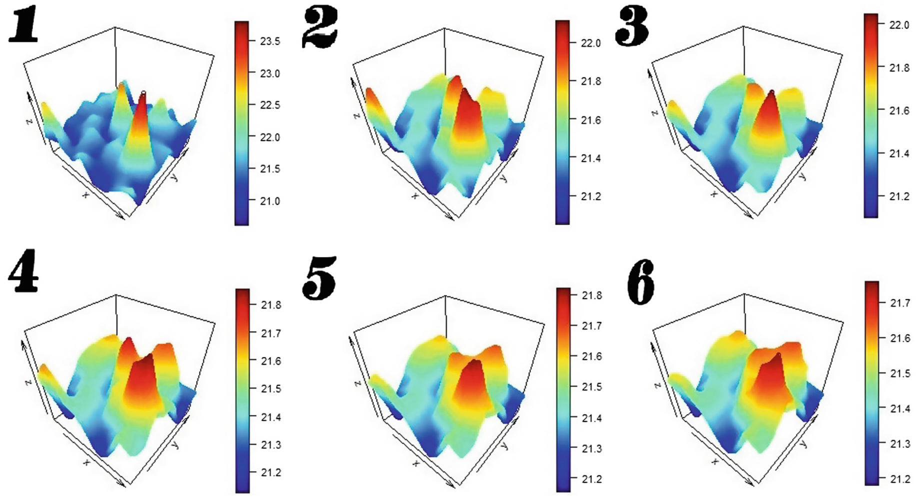

Fig. 2. Evolution of surface temperatures over the different steps in the game until reaching game equilibrium.

In Fig. 2, the first image shows the initial temperature and in the rest of the images the iterations of the game until the GE is reached. In the successive images, the temperature clusters are being formed, this can be observed by the changes in the colour gradient. It can also be seen that some areas with inaccurate temperatures self-correct smoothly on the basis of the temperatures in their environment. This is the intended process, since the game is executing its iterations depending on the environment surrounding the sensor. This makes sense because the temperature of the sensor will be similar to the average temperature of the environment in which it is located. Also, we show the evolution of the temperature on the surface. To this end, we have represented the temperature on the z axis to facilitate visualization in the form of a surface.

Experimental results about convergence and sensors that are providing inaccurate measurements are shown in Fig. 3. In the graph on the left it can be found that the algorithm reaches the diffuse convergence defined in this paper (i.e., 80% of the elements of the matrix reach convergence). The algorithm takes less than 10 steps to produce reliable temperatures relative to their neighbors. On the other hand, on the right side of the figure, the number of sensors that are performing inaccurate measurements (assuming a 0.01 °C error) is 15%. While in 10 stages of the algorithm this number decreases below 5%. The algorithm increases the number of sensors that are providing precise temperatures according to their neighbors in less than 10 steps.

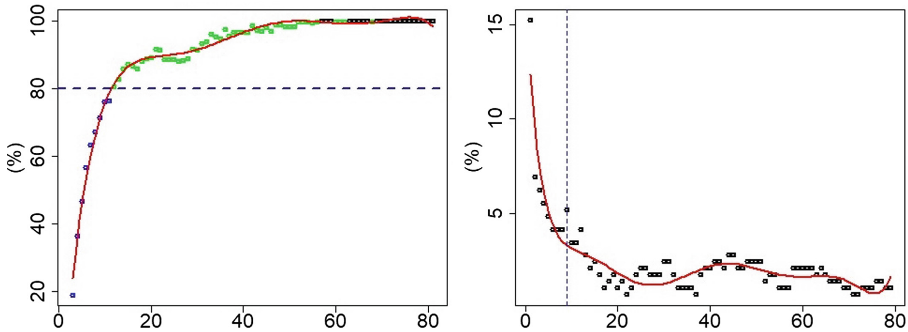

Fig. 3. Left: The algorithm achieves convergence in less than 10 steps. While from the 50 stages onwards the temperatures reach the optimal temperature regarding to their neighborhood. Right: Assuming that we have allowed an error of 0.01 °C, at the first step of the algorithm one notices that 15% of the sensors are providing inaccurate temperatures. Once 10 stages of the algorithm have occurred, sensors that are sensing imprecise temperatures are under 5%.

6 Conclusions

This paper presents a distributed and self-organized cooperative algorithm using game theory. The algorithm has been applied to data collected by IoT e-health devices. In addition, a blockchain-based architecture is suggested to improve data security. The novelty of this architecture lies in the fact that it provides an edge computing layer in which the cooperative algorithm is executed to improve data quality and the detection of false data. On the other hand, this new algorithm improves the energy efficiency of healthcare facilities by applying algorithms in the edge computing layer.

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