On using a distributed approach for help in medical diagnosis with wireless sensor networks

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Abstract: In this paper, we focus on providing new tools to help doctors in their diagnosis. We study the feasibility of using a distributed approach over Wireless Sensor Networks (WSN). We define a Wireless Body Area Network (WBAN) as a set of wireless sensors which equipped a patient. Each sensor senses a health parameter, for example, temperature or heart pulse. Our aim is to understand how a distributed approach can be a fair alternative to the common centralized paradigm. We study a distributed approach based on the token paradigm. Then, we compare this approach to the centralized one, throw simulations and experimentations over real sensors.

1 Introduction

In recent years, we assist to the growth of wireless sensor networks (WSN) fields of application. Wireless sensors provide a new way to perform some common or unusual tasks. Typically, wireless sensors can be deployed in wild areas to monitor some environmental changes, like temperature changes or luminance changes. They can also be plugged on animals to study how they evolve in their natural habitat. A well-studied field is patient monitoring. In such a context three main scenarios are underlined. The first one consists in monitoring patient over an emergency site (in-situ monitoring), the second corresponds to an in-hospital monitoring scenario, and finally, the latter consists in monitor individuals at their home (in-home monitoring). Our work takes part of the National ISIS Project which aim is to provide new tools to help doctors in their diagnostics, especially in an Intensive Care Unit (ICU). This project is composed of three main axes, a) the design of new algorithms including some artificial intelligence, b) data mining processing for health monitoring c) and the use of novel technologies for patient monitoring. We worked on providing novel technologies for patient monitoring and we focussed on a distributed approach to suggest some diseases over a wireless sensor network. In patient monitoring, the individual is commonly equipped with a great number of elements which allow to monitor several health parameters. We collaborated with doctors and nurses from the Zobda-Quitman hospital of Martinique. One of the problems underlined by the medical staff refers to the hardly practical side of the current equipments. WSN overcome this issue and provide a wireless and usable equipment. For instance, the patient would be able to easily pass medical examination outside his room with continuous monitoring. Furthermore, most of the currently used equipments are based on proprietary software environments. Contrary to those equipments, WSN can run personalized algorithms which can then be fit to some specific requirements. Requirements can concern the patient, for example if he has some specificity, or the care, for instance if new rules or methods should be applied in the diagnostic process. Moreover such a system would also consider mobility and medical staff would be able to ask for patient data via a mobile equipment.

We propose a formal definition of a disease and a distributed approach for help in medical diagnosis with WSN. The idea is to dedicate some master motes to the detection and to regularly update the set of the master motes. Our solution is based on the token paradigm. This paper is organized as follows, in section 2 we discuss some related work in the field of medical monitoring or distributed events detection. In section 3, we draw our context and introduce some definitions. Section 4 and 5 detail our contribution composed of the centralized approach as well as the token based one. Section 6, details the simulations and experimentations we performed and outlines the obtained results. In the last section, we conclude and draw some perspectives.

2 Related work

One of the earliest approach for patient monitoring with WSN relies on a centralized paradigm. Indeed, the sensors are solely deployed to sense health parameters values and to forward these values to a dedicated base station (BS). Then, the base station is in charge of the analysis of the received data. Even if data filtering mechanisms are performed under the sensors, the computation power of the nodes is not well used. Afterwards, many works focus on the detection of abnormal situations in a distributed manner [GGM$^+$07, PKR$^+$05, YC08]. Most of these works are not dedicated to medical monitoring but we notice that they can be applied in such a context. In [GGM$^+$07], the sensors which have detected an abnormal situation organize themselves dynamically, building a spanning tree over the existing network. This spanning tree allows the sensors to optimize the transmission of their measurements to the base station. In the specific medical field, complete architectures are generally studied. In [BV07] the authors propose algorithms to detect or prevent someone's long periods of inactivity at home. AlarmNet (Assisted-Living And Residential Monitoring Network) [WVD$^+$06] is an architecture for medical sensor networks which allows to monitor patient at home. In AlarmNet some alarms are raised in emergency situations (for example if the patient falls down). MiTag [GPS$^+$08] and Wiisard [KCB$^+$06] focus on monitoring people over an emergency site. Here, one of the challenges is to treat a large number of casualties and to ensure that each patient can be efficiently monitored. Several mechanisms are deployed to ensure that the data sensed by a WBAN are effectively forwarded to the equipments of the medical staff (personal digital assistant or laptop computer), so that the patient can be treated. An interesting point is that a mote can reconfigure itself. An example is the modification of the data transmission rate according to some specific context.

In-hospital monitoring generally provides a controlled environment with a fixed infrastructure. The goal is to monitor a patient anywhere during his hospital period. Codeblue [SCL$^+$05] is a complete infrastructure for in-situ and in-hospital monitoring. It provides a publish/subscribe architecture which allows doctors or nurses to register to any particular event (new data from a given patient or an health parameter which has reached a given threshold) using a mobile wireless equipment. CodeBlue also provides a RF-based location tracking to locate patients in the hospital. In all these frameworks and algorithms, most of the computations are not done on local sites but the sensed data are sent to a base station where all data are analysed.

3 Wireless body area network: diagnosis problem formulation

3.1 Motivation

In medicine, a disease is commonly detected if a set of symptoms is verified. These symptoms can be verified thanks to blood analysis results or by observing the patient behavior (vomiting, headache or for example). In other cases, this symptoms rely on the fact that some health parameters (heart rate, electrocardiogram, temperature or blood sugar) have reach some improper values. Let's take the example of the gastroenteritis. A patient has the gastroenteritis if the following symptoms are verified: a) diarrhoea, b) fever, c) headaches, d) vomiting, e) loss of appetite, f) abdominal cramps. In this case only one symptom (fever) can be sense by a transducer. We focus on such symptoms and intend to suggest some diseases. Even if the example we presented is quite simple our model is designed to handle more complex disease definitions. The health parameters values are traditionally sensed by transducers which equipped the patient and which are linked to a specialized engine. First works that have been performed on the use of WSN in medical care, rely on such a centralized approach. A patient is equipped by a set of motes (a sensor linked to transducers) and each mote measures some health parameters. Typically, all sensed values are sent to a base station which perform all computations, analysis and detections. This centralized paradigm leads to some drawbacks. First, routing mechanisms have to be implemented in order to ensure that all the information sensed by the sensors is transmitted to BS. Second, the BS failure implies that no detection is possible anymore. In a fine-grained multi-hop network, highly prone to congestion it remains difficult to ensure a real-time detection needed in an intensive care unit. In the context of in-hospital monitoring, we can suppose that each wireless body area network transmits the data to a wired network responsible for forwarding it to the base station. Nevertheless, as our work is not only dedicated to a medical context, we take in account this issue.

We propose a distributed approach which eliminates the risk of bottleneck. The aim is then to allow the motes to act together in order to establish a common diagnosis. In this solution any mote can be responsible for detecting a disease. We designed a distributed algorithm for patient monitoring and have conducted several experimentations to evaluate its reliability and its efficiency.

3.2 Definition

The overall context is the following, each patient is equipped with a wireless body area network composed of several wireless sensors. We consider that each sensor is only linked to one transducer. We denote $\mathbf{S} = \{\mathbf{s_0}, ..., \mathbf{s_{n-1}}\}$, the set of motes on a patient. Each mote s_i senses the health parameter v_i. Thus, $\mathbf{V} = (\mathbf{v_0}, ..., \mathbf{v_{n-1}})$ represents the set of sensed health parameters for the patient.

DEFINITION 1 *We define a disease as a vector d_j describing which B_j health parameters have to be supervised to detect the disease, an integer k_j which represents the minimum number of thresholds to be reached in order to decide whether a patient has the disease and a set C_j which gives the critical range for each sensor.*

The integer k_j is the critical threshold of the disease d_j. *The vectors B_j and C_j are such that:a) $d_j = (b_0^j, ..., b_{n-1}^j)$, $b_i^j = 1$ if v_i has to be supervised to detect the disease, and $b_i^j = 0$ otherwise, b) $C_j = (c_0^j, ..., c_{n-1}^j)$, c_i^j is a range.*
The set of the diseases which can be detected by the motes is denote $\mathbf{D} = (\mathbf{d_0}, ..., \mathbf{d_{p-1}})$.

Let us consider that a patient is equipped with three wireless sensors such that, $S = \{s_0, s_1, s_2\}$ and $V = (v_0, v_1, v_2)$. We take a disease d_0 which occurs if the health parameter v_2 is greater than 37 and if the health parameter v_1 is between 20 and 28. The disease d_0 is only concerned by the health parameters sensed by s_1 and s_2. Thus, $d_0 = (0, 1, 1)$ and $B_0 = 2$. The set of critical thresholds is $C_j = (]37, +\infty[, [20, 28])$.

DEFINITION 2 *The value sensed by a mote s_i is a critical value for the disease d_j if and only if it belongs to the critical threshold c_i^j.*

We denote $\theta_{\mathbf{i}}^{\mathbf{j}}(\mathbf{t})$ a boolean value which indicates if s_i has sensed a critical value for d_j at the time t. The number of reached thresholds for d_j at the time t is $\mathbf{\Theta_j(t)}$. Moreover, $\beta_{\mathbf{i}}(\mathbf{t})$ is equal to 1 if the mote s_i has sensed a critical value for at least one disease at the the time t. $\beta_{\mathbf{i}}(\mathbf{t})$ is equal to 0 otherwise.

Proposition 1 *A disease d_j is detected at the time t if and only if, k_j motes over B_j have sensed a critical value for d_j, at the time t. That means, a disease d_j is detected at the time t if and only if: $\Theta_j(t) \geq k_j$.*

DEFINITION 3 *An on-time detection (*OT detection*) is a detection performed within the slot where the disease appears. In other words, if a disease appears at a time t and is detected at the time t by the motes, so the detection is said on-time detection. Otherwise we say that the detection is non on-time (this detection requires more than one slot).*

4 Design of the centralized algorithm

A centralized approach consists in forwarding the raw data to a base station. The base station is usually a wired equipment in charge of the analysis of the received data. The computations are made over the base station and this latter is able to determine if some diseases occur. We detail our centralized algorithm where time is divided into slots. At each slot, motes sense new values and forward them to the base station. Once a message is sent, the mote turns off its radio unit until the next slot. The base station verifies if a disease occurs and raises an alarm if necessary.

We give the example of a network of five motes which equip a patient in order to diagnose the sepsis disease (d_0). The sepsis disease is a whole body inflammatory caused by an infection. We have $S = \{s_0, s_1, s_2, s_3, s_4\}$ and $V = (v_0, v_1, v_2, v_3, v_4)$. v_0 is the body temperature, v_1 is the heart rate, v_2, the blood pressure, v_3, the white blood cell count and v_4 the blood sugar. We assume that a patient has the sepsis disease if two of the following symptoms are verified: a)temperature $\in t_0^0$ = $]-\infty, 36[\cup]38,3,+\infty[$, b) heart rate $\in t_1^0$ = $]90,+\infty[$, c) blood sugar $\in t_4^0$ = $]7,7,+\infty[$ d)white blood cell count $\epsilon\ t_3^0$ = $]-\infty, 4000[\cup]12000,+\infty[$. Thus, $d_0 = \{1,1,0,1,1\}$, B_0 = 4 and $k_0 = 2$.

An execution of the centralized algorithm is illustrated by Figure **??**. Notice that in our implementation motes remain inactive (sleep mode) until they have to send their data to the BS. In the first slot (Figure **??**(a)), only one mote has sensed a critical value for the sepsis. This is represented by a the 1 value over the arrow. Then, no alarm is raised. The value of Θ_0 is reset at each slot and in slot 2 (Figure **??**(b), two motes have sensed a critical value ($\Theta_0 \geq 2$). So, the base station raises an alarm.

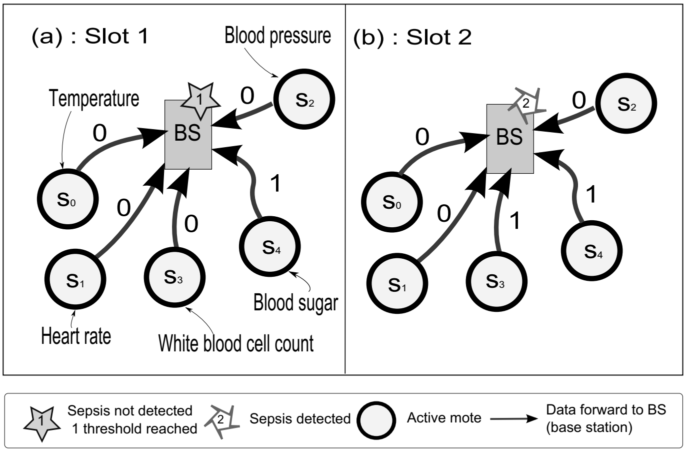

Figure 1: An execution of the centralized algorithm

5 Design of the distributed algorithm

This section presents the token algorithm that we designed for diagnosis computation over wireless sensor networks. This approach introduces two kinds of motes: the master motes and the non-master motes. A master mote is in charge of detecting one or more diseases, while a non-master mote only transmits its data to the master ones. A token is defined for each disease, and then, the mote which owns the token will be able to diagnose the given disease. We introduce the set E, which is a set of tokens in the network and the set S' of masters motes. These two sets are defined as follows: $E = \{e_0, ..., e_{p-1}\}$, where e_j corresponds to d_j and $S' = \{s_i / s_i \in S, \exists\ e_k, s_i$ owns $e_k\}$. Each token is assigned to a mote at the beginning of the algorithm. We call F the tokens exchange frequency. A procedure is run every F slots to perform the token exchange. Each mote has a score which indicates the probability of being master according to the last time and the number of times it has been master. Since any mote may become a master, then we store locally on each mote the definition of all possible diseases. This lightens the token exchange procedure since the masters motes have not to transmit the whole disease definitions to the new elected motes.

The masters motes always remain in an active mode, while the non-masters motes go in a sleeping mode once they have sent their information. As previously, the time is divided into slots. At the beginning of each slot the motes sense new values (throw the ReadMeasure() procedure). Once they have sensed their values, the non-master motes (cf algorithm **??**) verify if this value is critical for each disease they involve in. A mote k wakes up to send to the masters a vector containing the values of the θ_j^k, $\forall j$ if this is the first slot ($t = 0$) or if it has sensed a critical value for at least one disease ($\beta_k(t) = 1$). Afterwards the mote k remains in a sleeping mode until the next slot. A mote k' such that, $\beta_{k'}(t) = 0$ keeps itself in a sleeping mode.

A master motes h begin a slot similarly than the non-master motes. It senses a new value and compute θ_j^h for each disease it is responsible for (cf algorithm **??**). A master also maintains the counter Θ_j, so that it can determine at each slot t which disease occurs. So, once a master mote has updated the counters corresponding to the diseases it can detect, it raises an alarm if at least one disease is detected. The alarm message sent by a master mote indicates all the diseases which may occur. During its active mode a master mote waits for messages from non-master motes. Master motes use the procedure ListenForMessages() to deal with incoming messages. When it receives a message, a master mote s_h updates its counter Θ_j, $\forall j$ such that s_h owns e_j. Then, it verifies if there a disease and raises an alarm if needed.

Algorithm 1 Non-masters side

```
for each slot $t$ do
    $\beta_k(t) = 0$
    m=ReadMeasure()
    for each $d_j \in D$, $b_k^j == 1$ do
        if $b_k^j == 1$ then
            if m $\in c_k^j$ then
                $\theta_j^k(t) = 1$
                $\beta_k(t) = 1$
            else
                $\theta_j^k(t) = 0$
            end if
        end if
    end for

    if $(\beta_k(t) = 1)$ or $(t = 0)$) then
        WakeUp()
        BroadcastToMasters()
        SleepDown()
    end if
end for
```

Algorithm 2 Masters side

```
for each slot $t$ do
    $\beta_h(t) = 0$
    m=ReadMeasure()
    for each $d_j \in D$, $s_h$ owns $e_j$ do
        if $b_h^j == 1$ then
            if m $\in c_h^j$ then
                $\theta_j^h(t) = 1$
                $\beta_h(t) = 1$
                $\Theta_j(t) \leftarrow \Theta_j(t) + 1$
            else
                $\theta_j^h(t) = 0$
                $\Theta_j(t) \leftarrow \Theta_j(t) - 1$
            end if
        end if
    end for
    if $\exists\, j$ such that $\Theta_j(t) \geq k_j$ then
        RaiseAlarm()
    end if
    ListenForMessages()
end for
```

Notice that each mote waits a random time before sending its data to the masters. Some message can still be lost but, as we see before, the time is organize into slots. So, if a disease is not detected into a slot, it can be detected into a slot after. As a disease appears more than 1, our algorithm is able to detect it even if the detection is non on-time. Typically if a slot spreads over 1 second, its clear that, a symptom does not reveal only during a second.

To illustrate our algorithm, the sepsis example is detailed in the following. We consider the network of five motes gives in Figure **??**. The mote s_2 owns the sepsis (d_0) token although it is not involved in d_0. Indeed, the health parameter sensed by s_2 is not required in any symptom of d_0. The two master motes s_0 and s_2 remain in an active mote. For better understanding, we only consider the detection of the sepsis in our example.

In the first slot (cf Figure **??**(a)), all the motes which participate in the sepsis send their information. None of them has sensed a critical value. Thus, Θ_0 is equal to 0. In the slot 2 (cf Figure **??**(b)), s_1 has sensed a critical value for d_0. It sends a message to the master motes and only s_2 handles the message. The value of Θ_0 is equal to 1. The mote s_3 senses a critical value for the sepsis, at the next slot (cf Figure **??**(c)) and the value sensed by s_1 is no more critical. The value of Θ_0 remains the same. Finally, in the slot 4(cf Figure **??**(d)), the sepsis is detected since s_0, s_3 and s_4 have sensed a critical value and $\Theta_0(4) \geq k_0$.

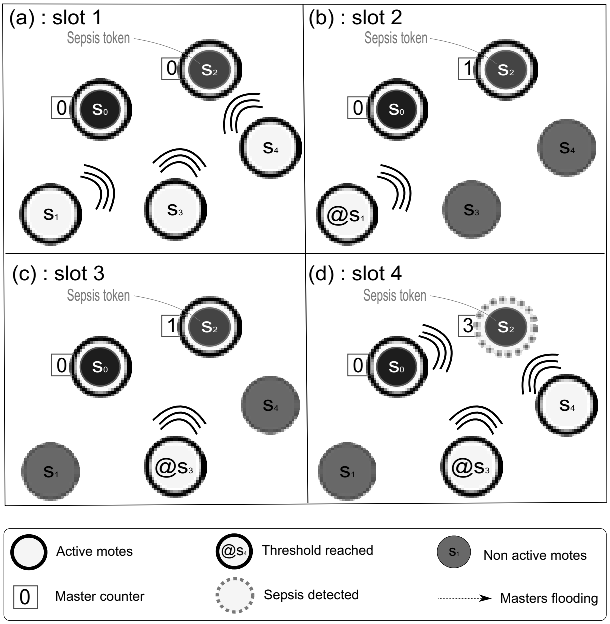

Figure 2: An execution of the token algorithm

6 Simulation and results

We intend to propose a distributed approach for medical diagnosis using wireless sensor which is a relevant alternative for existing approaches. All the simulations and experimentations we performed were designed to determine our distributed approach is robust and reliable compare to the centralized one. We also studied the energy consumption for the two approaches.

6.1 Tossim simulations

The token algorithm has been implemented using the TOSSIM [LLW+03] toolbox which is an emulator for wireless sensor network using TinyOS [LMP+04]. TinyOS is an event-based operating system written in a C-like language call nesC. We have conducted two kinds of experimentations with TOSSIM. We first consider a network composed of 50 motes. The parameters are as follows: $S = \{s_0, s_1, ..., s_{49}\}$, $V = \{v_0, v_1, ..., v_{49}\}$, $D = \{d_0\}$, $\forall i, b_i^0 = 1$, $B_0 = 50$, $k_0 = 35$, $F = 10$. We run the simulations over 250 slots and the slot size (Z) is equal to one second. The disease d_0 appears 250 times, then there is a disease to detect at each slot. Each experimentation is run over 100 ties.

Token exchange frequency

$\rightarrow$ *Detection rate and on-time detection rate.* The first experimentation consists in evaluating the impact of the token exchange frequency F on the detection rate. The exchange frequency varies from 1 to 50. If F is equal to 10, the master motes leave their tokens every 10 slots. Figure **??** shows the detection rate for each value of F. A bar in the histogram indicates the detection rate.

We notice that when the F value is set to a high frequency (1s) the detection rate is very low and d_0 is detected only 2% of the time. The detection rate increases with the value of F and reaches 98% while $F = 50$. We noticed also that failed detections mainly occur during the slot when the tokens are exchanged. Indeed, the exchange procedure uses a large time part of the slot duration. This observation explains why the detection rate decreases when F increases.

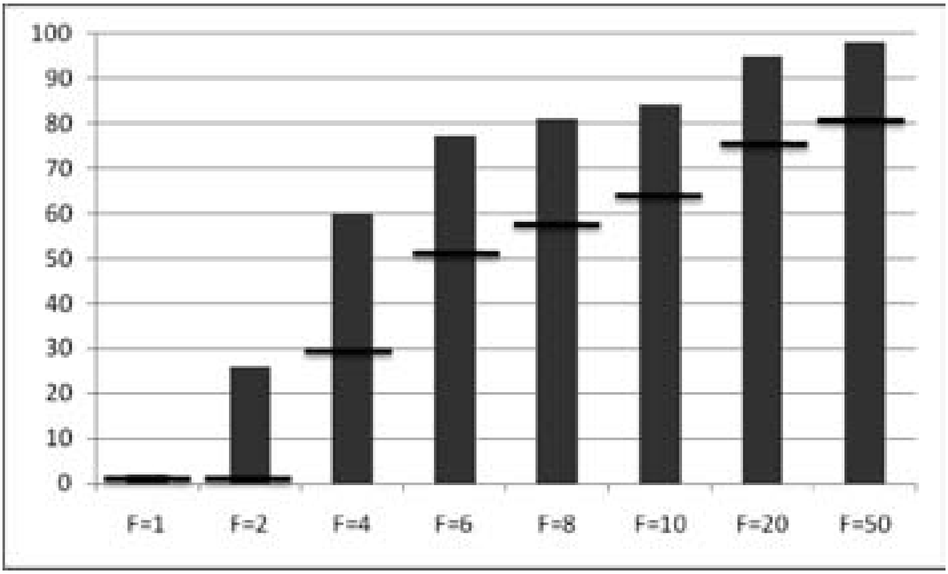

Figure 3: Detections rate depending on F value

We have also evaluated the on-time detections rate. Figure **??** shows the obtained results. The on-time detection rates are indicated by a horizontal bar in the figure. The OT detection rate is always greater than 80% while $F \geq 6$. As previously, we notice that all the detection which are non on-time are due to the token exchange mechanism. So, the OT detection rate increase with the token exchange frequency.

Number of motes

→ *Detection rate and on-time detection rate.* In the second experimentation, we compare the token algorithm performance with the centralized algorithm performance. We keep the parameters given above. The critical threshold of d_0 is initially set up to 10% of motes number, that is 5. Then, we updated the value of k_0, from 25 to 50 motes. Figure **??** shows the detection rates performed for each value of k_0 as well as the on-time detection rates.

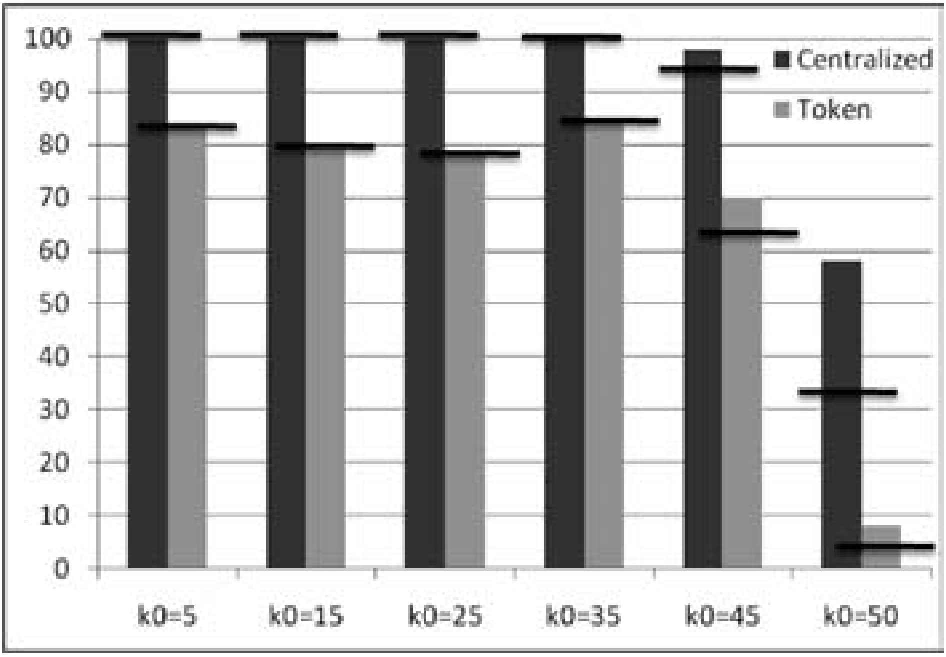

Figure 4: Detections rate depending on k_0 value

The token algorithm achieves a detection rate 20% lower than the centralized one. Even if it allows to diagnose the disease in 80% of cases, the failed detections have to be prevented. We intend to enhance the exchange procedure in order to allow the motes to diagnose the disease even in a slot when the exchange occurs. Nevertheless almost all detections which are performed are on-time for both approaches. This gives promising results.

6.2 MicaZ experimentations

We have also implemented our approach over real motes. We use micaZ motes from Crossbow. The motes were place over a rectangle of 80 cm x 20 cm. We studied the energy consumed to achieve the two algorithms (centralized and token). As the experimentations run over two hours the energy lost we observe is very low. Nevertheless we can notice that the token algorithm uses more energy to detect a disease. Table **??** gives the accurate voltage lost values for each motes. Obviously the motes which most often become masters show a bigger voltage lost than others.

The token algorithm necessitates much more energy by mote, with an average of 13,25 joules . Indeed, it uses on average 6 times greater than the centralized approach which necessitates 2 joules by motes . This is our first results and we intend to perform another experimentations to improve the energy management in the token algorithm.

Table 1: Energy level by mote

Algorithm	s_0	s_1	s_2	s_3	s_4	Energy dissipation
Token	-0,1 V	-0,06 V	-0,07 V	-0,07 V	-0,07 V	53 J
Centralized	-0,01V	-0,02V	-0,01V	-0,01V	-0,02V	8 J

7 Conclusion and future work

We investigated a completely distributed approach for help in medical diagnosis using wireless sensor networks. We have shown that, even if this method consumes more energy than a centralized approach it can constitute a great alternative. As far as we know, this is the first time that decentralized solutions are presented to compute diseases in a medical environment, unlike used centralized systems. We have used the definition of a disease which corresponds to a set of defined thresholds in our context. Regarding to the number of reached thresholds at a defined time we can determine if a disease may occur or not. In this work we investigated the use of sensor networks in a real word life. We have shown that the use of distributed algorithms may solve many practical problems with a certain efficiency. This study could be generalized for many other areas (fire forest detections, swimming pool assistance, ...). Some issues will be investigated in the next future, in particular the energy consumption. We think that the energy consumption can be reduce thanks to special mechanisms. For instance we will work on a new way to set up the token circulation because most of the energy is consume during this step.

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