DESIGNING A REAL-TIME HAND HYGIENE MONITORING SYSTEM FOR HAI PREVENTION

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Getting an infection inside the hospital from the environment or from persons such as patients, physicians or visitors is known as the Hospital Acquired Infection (HAI). HAI is classified as one of the main issues which hospitals face nowadays that increases the mortality rate within hospitals. It also requires a large financial budget to be combated.

In this paper, we propose a system dedicated to monitoring the hand hygiene rules within a hospital room, by tracking the positions of both physicians and patients, and by measuring the hand hygiene duration.

Keywords: smartband, hand hygiene rules, Hospital Acquired Infection (HAI), medical workflows monitoring

1. Introduction

Nowadays, in hospitals, the HAI problem is considered a big challenge and one of the most important factors which causes people's death. It has a high position within the hierarchy of the first ten causes of people's death [1], [2], the mortality caused by HAI exceeding the mortality caused by some kinds of cancer. Europe and USA have high HAI rates, around 5-15% of patients getting a kind of infection inside hospitals and around 9-37% of patients getting an infection inside hospital's ICUs (intensive care units) [2]. The infection rate in hospitals ranges from 4.6% to 9.3% [3], [4].

In Europe, around 5 million people get an infection each year and 2.7% of them die annually [1], [2], [5], [6]. The HAI problem causes a financial burden ranging between 13–24 billion Euros and prolongs the period of patient staying within hospitals up to 25 million additional days per year [5].

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In 2002, in U.S.A, the HAIs rate was around 5% of the hospitalized patients. The financial cost caused by the HAI problem gets to 4 billion dollars, with around 100.000 deaths per year [2], [5], [6] [7].

The annual rate of HAI is 4.4% in India [8], [2]. In Argentina and Turkey, the HAI rate was more than 50 for each 1000 days of hospitalization within hospitals ICUs [9], [10].

Various reasons could cause the HAI, such as an insufficient and inappropriate staff training, lack of equipment and neglect of maintenance [1], [2], contaminated surfaces, clothes and equipment [2], [11] the respiratory and mechanical ventilation associated infections [2], [12], an inappropriate air flow within the hospital rooms [1], [2], [13], lack of strategies and necessary policies for preventing the HAI [2]. Among these reasons, contaminated hands represent the crucial factor in spreading the infection, studies revealing that they cause around 19.000 deaths annually in U.S.A [1], [8], [14], [15].

We designed a system whose aim is combating HAI. At the moment of writing this article, a system's prototype is implemented, its aim being the monitoring of one hospital room. The system tracks the compliance of physicians and patients with hand hygiene rules, encouraging them to comply with the hand hygiene rules by issuing alerts.

2. Traditional and ICT solutions

Among the traditional solutions of combating the HAI are:

- following the proper procedures of sterilization and cleaning;
- providing and cleansing the medical equipment before and after usage and then storing them in specific places; disposable medical products are preferable to the reusable ones;
- periodical maintenance of medical equipment and of the healthcare buildings [13], [16];
- providing a feedback to the management team about the medical workflows, for evaluating of the HAI status and finding proper solutions [17];
- providing the needed resources permanently, such as masks, tissues and disinfectants;
- applying the isolation principle by leaving a suitable space between patients' beds and isolating patients who have the same disease in the same place [13], [18];
- various personal procedures should be taken into consideration by both patients and physicians to reduce the HAI, such as taking care of personal hygiene, particularly the hair and nails, wearing gloves and masks, using towels and tissues only once, covering the face and head entirely [5], [7];
- monitoring precisely [17] the prescribing and usage of the antibiotics;
- using a suitable filtration system to get rid of the polluted air [13];

- following the appropriate procedures for preparing the operating room, such as sanitizing the whole room [13], using double gloves, water proof clothes and sanitizing the whole patient's body, covering it excepting the specific part for performing the operation [18], [19];

Various solutions were applied for combating the HAI and many technologies were adopted for performing this purpose. Different sensors were used to monitor, make measurements and read the environmental parameters. A motion sensor was used to sense the physician’s hands when they were put inside two dedicated gaps of a device, which provides soap and water for washing or hot air for drying [1], [2], [20].

Some solutions are based on battery powered badges provided with ZigBee or RFID technology, so that some ZigBee monitors connected wirelessly to the ZigBee badge were distributed in some locations for collecting the patient’s parameters. RFID readers can be fixed in some places such as doors, sinks and alcohol bottles for reading the medical staff’s ID stored in their RFID tags and thus identifying each person uniquely. Transceivers were used to transmit the gathered data to a server, and in some solutions a screen was used for prompting the staff to follow the hygiene protocols [1], [2], [6], [7]. RFID readers and tags were used in hospitals to recognize all persons, including patients, for obtaining their vital parameters and thus detecting whether they are infected or not, to monitor the infected hospital wards and locations permanently [1], [2], [20].

The Intelligent M system [21] is based on a smart band provided with motion sensors, RFID reader and a battery. A number of RFID tags are located in different places within the monitored environment. This system is dedicated to monitoring the hand hygiene protocols, and by issuing alerts it can urge the medical staff members to comply with the correct hygiene rules including the hands motions, the sanitizing duration and the five moments required for hand hygiene. The system issues alerts in case of breaking the hand hygiene rules [1], [2], [21], [22], [23].

The BioVigil System [24] is composed of a battery powered badge with alcohol sensor and a ZigBee transceiver connected to a remote server. The alcohol sensor is able to detect the antiseptic materials after touching the badge to decide whether the medical staff member has disinfected his/her hands or not. The system has the ability of issuing alerts at breaching of the specific hand hygiene rules [1], [2], [24], [25].

MedSense Clear system [1], [2], [26] is composed of a number of wirelessly connected components. Each physician wears a badge like an identity card. The beacon and the dispenser monitor, which are placed at each patient's bed, collect data about the usage of the disinfection dispenser and send them to the badge. The physician is alerted by the badge if he/she missed the opportunity for hand hygiene. The data from the badge is automatically uploaded to the base station when the physician is in its proximity, and then sent to the MEDSENSE HQ, a web based reporting tool. MEDSENSE HQ visualizes the hand hygiene compliance data of each medical staff member, in a user-friendly dashboard format.

3. Our proposal for a system dedicated to monitoring the compliance of the hand hygiene rules

The aim of the proposed system is to prevent the HAI by fighting with one of its most important causes, which is the contaminated hands, and thus reducing the HAI spread.

3.1. Functional requirements

The system is intended to monitor the medical staff members' activities inside a hospital room, by identifying their location within the room in real-time and recognizing whether they are following the correct hand hygiene rules at the appropriate moments. At the same time, the system will ensure the monitoring of the patient's entry into the toilet and their compliance with the hand hygiene rules after going out of the toilet. The system is also designed to help the medical staff members to follow the hand hygiene protocols by issuing alerts in case of breaching the predefined hand hygiene rules. We consider that each room has a hand washing sink and a separate toilet for patients. The doctors and nurses should wash their hands when they enter the hospital room, before and after treating each patient.

The main use case scenario of our system is based on a normal sequence of events. It starts at the room entrance, when a physician (doctor/nurse) enters the room and the system recognizes his identity. After entering the room, he goes to the sink to wash his hands before doing any other action, then he goes towards a patient to care him. After that, he goes again to the sink to sanitize his hands before going to the next patient. The physician cares the next patient and then he goes again to the sink to disinfect its hands.

The system monitors the period of physician's stay at the sink, which should correspond to the period needed for correct hands washing (the "Five Moments" for Hand Hygiene [3]).

When one of the patients enters the toilet, the system recognizes his identity, and when the patient comes out of the toilet he goes to the sink to wash his hands before going back to his bed.

The system should monitor the compliance with the hygiene rules by the medical personnel and store the collected data to a central station. The system should also issue alarms to notify them when they fail to comply.

3.2. Non-functional requirements

- Ease of deployment: the system should be very easy to install and configure.
- Ease of use: the system should not require special operations to the physicians or patients.
- The system should not obstruct the normal hospital activity. The system will not break or overcharge the normal hospital activities.

3.3. The hardware architecture

The hardware components must meet the following requirements:

- identify doctors and patients
- identify the positions of the doctors and patients in the room
- monitoring the compliance with hand hygiene rules
- storing the monitored data for further analysis

To satisfy the first two requirements we have chosen the RFID technology.

RFID is one of the most important IoT (Internet of Things) technologies [27], [28]. It enables identifying people and objects [2] based on unique numbers stored on microchips (RFID tags). RFID uses radio waves for the wireless communication between RFID readers and RFID tags. The two hardware components of an RFID system are:

- the RFID reader (transceiver or interrogator), which is responsible to generate a radio frequency field, transmit radio waves and scan the tags in its area. After building the connection, it can read data from and write data to each tag within the range;
- the RFID tag (transponder), which is attached to the daily objects to make each of them identifiable. It can receive the reader's signal (request) by its own antenna and send back the ID number or other kinds of data that it can store [28], [29], [30], [31];

Thus, each special location from the room, i.e. the room entrance, each bed, the sink and the toilet entrance, will accommodate an RFID tag. Every physician and patient will wear an RFID reader. The data acquired by the RFID reader are sent to a PC to be analysed and stored for further analysis. For the transmission of data acquired by each RFID reader to the PC we have chosen the ZigBee technology.

In low-power applications, where the devices are powered by a battery and the lifetime is an issue, specific data transmission protocols are used. ZigBee is a simple and low-cost routing protocol suited for equipment that requires short-range (10m-70m), low-rate wireless data transfer [32], [33], [34]. ZigBee technology provides reliability and security and is used particularly for home automation and healthcare monitoring applications [33], [34]. It has an authentication mechanism; also each delivered message has a reliability code that enables the receiver to check the message and detects any change [2].

A classical wireless sensor network implemented with ZigBee protocol contains three types of nodes (Fig. 1):

- a Coordinator: singular node that creates the network and receives all the data from the network;
- routers: intermediate the information transfer or transmit their own data towards the Coordinator;
- end-points: acquire data and transmit them towards the Coordinator; they can enter into sleep modes to save energy.

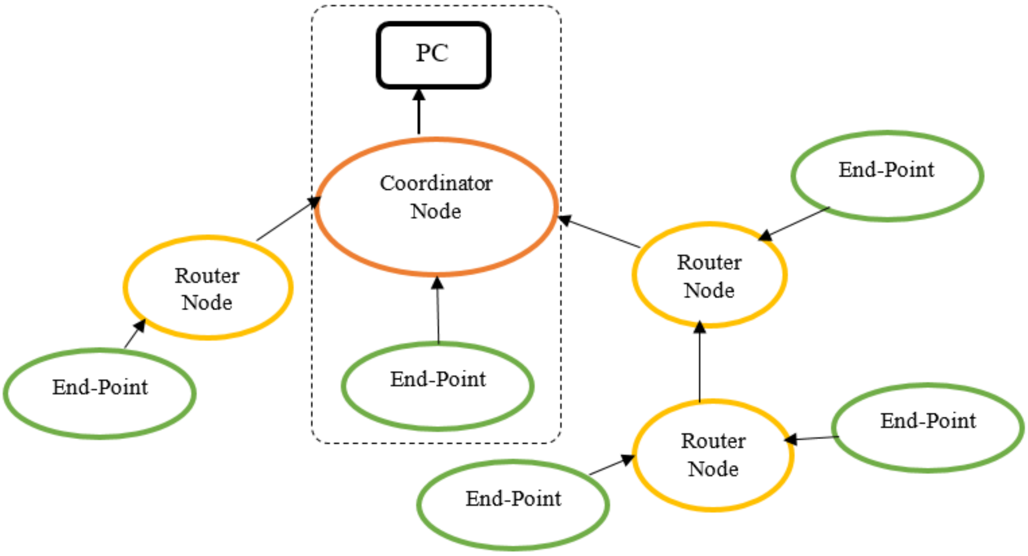

Fig. 1. The wireless network of our system

The Coordinator node acquires the data from the network and transmits it to the PC where it can be displayed and stored. The Coordinator and the PC, which together form the base station, can be placed in a server room of the hospital. In each room with patients, a router is placed, which receives data and transfers them towards the Coordinator. The people in the hospital (physicians and patients) have SmartBands, which act as end-points and send data about their activities to routers or to the coordinator. Each SmartBand contains an RFID reader and has a unique ID, which represents the ZigBee transceiver ID. The device is assigned to a certain physician/patient in the database implemented on the PC.

4. The implemented prototype

4.1. Operation

We considered a room with two beds (Fig. 2).

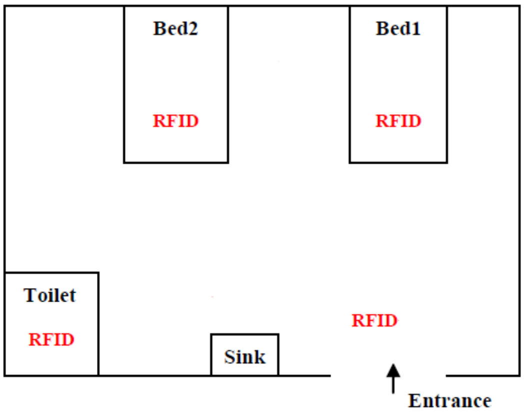

Fig. 2. The hospital room layout

The implemented prototype contains a Coordinator connected to a PC, a SmartBand associated to a doctor, and five RFID tags placed at locations of interest (entrance door, beds, sink and toilet). This is shown in Fig. 1, marked by a dotted rectangle. The architecture can be scaled from one room to an entire hospital by adding new components and extending the application running on the PC.

When it is powered on, the SmartBand connects to the network and transmits a packet, informing that the physician is active. The doctor name and other necessary information about him/her are displayed on the Graphical User Interface (GUI) of the application running on the PC.

The SmartBand is able to recognize the special locations by reading the RFID tags, and make the appropriate decision regarding the sanitation. A data packet is transmitted to the PC application to be displayed and stored.

The packet transmitted by the SmartBand to the PC is composed of some encapsulation bytes and data bytes. The structure of the data bytes is shown in Table 1. The transceiver address contains 8 bytes, the ID of the RFID tag of each location where the SmartBand holder is situated contains 12 bytes and the accelerometer data contains 6 bytes, 2 for each axis. The last byte is used to represent the decision made by the SmartBand regarding the sanitization: (sanitized, needs sanitization, no sanitized), which are displayed in green, orange and red on the GUI.

Table 1

Data packet format

Transceiver Address								RF-ID												Ax		Ay		Az		D
1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8	9	10	11	12	1	2	1	2	1	2	1

4.2. Alerts

When the physician enters the room, the wrist SmartBand starts to emit alerts. The SmartBand's led flashes orange color for 10 seconds, to remind and encourage the physician to sanitize his hands at the sink before doing any other action. If the physician ignores this alert, the led color turns into red till the physician arrives at the sink and starts sanitizing the hands. At the sink, the minimum period for sanitizing is 40 seconds. During this time the led blinks orange color. If the physician respects the dedicated duration of hands sanitizing, the led will turn to green. Otherwise, the led turns to red, reminding the physician to restart sanitization of his hands. When the physician is at the sink, the SmartBand acquires the movements of his hands by the accelerometer (two times per second) and sends the parameters of the three axes (x, y, z) to the PC application in order to be analyzed (this analysis is not implemented in the current prototype).

After finishing the hand hygiene at the sink, the physician goes towards one of the two patients. The physician's position is identified by reading the RFID tag mounted at each of the two beds and assigned to the patients. The GUI displays in green the patient's bed. After treating the first patient, if the physician doesn't go to the sink to sanitize his hands, the SmartBand led starts to blink orange flashes for 8 seconds, reminding him to comply with the hand hygiene action. If the physician ignores the alerts, the led color converts to red after 8 seconds. If the physician goes to the sink and starts performing the hand hygiene, the led color emits orange flashes for 40 seconds, then at the end of the 40 seconds, the SmartBand led color turns to green, which means that the physician's hands became sanitized. Then, the physician goes to the next patient with a green color on the SmartBand. The system can identify his position in the same way, and after treating the next patient, the physician should go to the sink to comply with the hand hygiene rules as previous and the alerting mechanism works in the same way.

The patients will have their own SmarBand devices with the same characteristics as the ones of the physicians. In our experiments, we used the same SmartBand to simulate both the physician and the patients; the flow for the patients regarding the identification of their locations and the alerting mechanism is the same as for the physicians.

4.3. The Graphical User Interface

The GUI of the application that runs on the PC displays the actions and the alerts for the physician (Fig. 3). The software is realized in LabVIEW programming language, a graphical language where blocks with various functions can be connected to perform complex tasks.

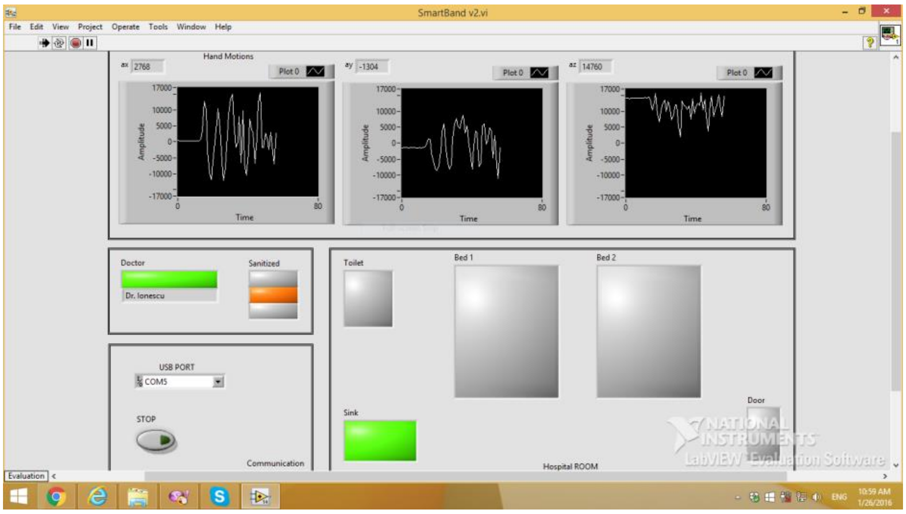

Fig. 3. The Graphical User Interface

The GUI has four areas.

The communication area (left-bottom) visualizes the connection with the Coordinator node. The USB port where the Coordinator is connected must be selected. This area also contains a button for turning the communication on or off, so that after clicking the button, the small arrow inside it turns to light green, which means that the communication is stopped, and turns to dark green when the communication is on.

The SmartBand holder area (left-center) gives information about the physician (the SmartBand holder). When a SmartBand connects to the network, the transceiver ID is transmitted to the Coordinator and the interface shows what physician is active (the physician's name). If the physician is authorized to make visits, a green indicator will appear; otherwise, the indicator appears grey and the name cell appears empty. The same area shows the alarms transmitted by the SmartBand using three indicators placed one above the other: the above one is colored in green when the SmartBand led is green, the middle one is colored in orange when the SmartBand led blinks orange light, the bottom indicator is colored in red when the SmartBand led emits red light. In this way, the GUI shows that the physician is complying with the hand hygiene rules, or not.

The hand motions area (top) displays the data sent by the accelerometer included in the SmartBand. The acquisition of hands motions is made only when the physician is at the sink, in order to analyze the hand motions.

The hospital room area (right-bottom) is a replica of the positions where the physician can be in the room: the door, the sink, the first bed, the second bed or the toilet. When one of these places turns to light green, it means that the physician is at that place and the other places are colored in grey.

4.4. The SmartBand architecture

We designed a SmartBand prototype with the needed functionalities for our system. It was developed based on a RedBoard system. This is similar to Arduino board and is equipped with an Atmel ATmega328 microcontroller that offers 14 digital I/O pins, 32k flash memory and 16MHz clock speed. The RedBoard is connected to an accelerometer, an RFID Reader and a ZigBee transceiver, as in Fig. 4.

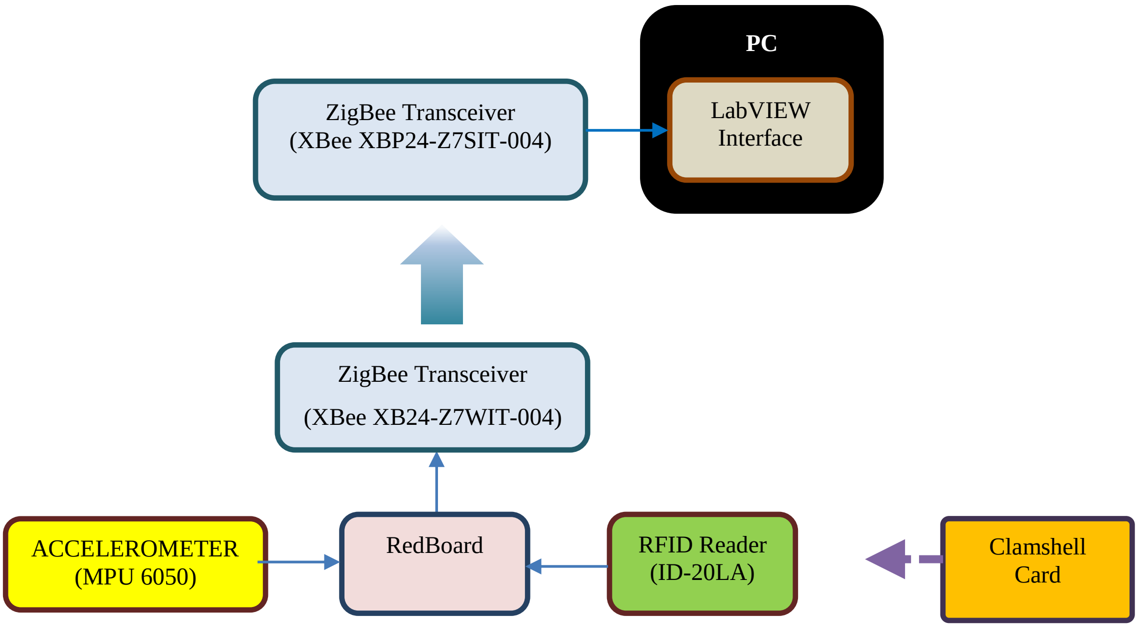

Fig. 4. The SmartBand architecture

We used an MPU 6050 accelerometer, which includes a gyroscope, needed for further development of acquiring precise hand motions. Communication with all registers of the device is performed using I2C at 400 kHz. The MPU 6050 features three 16-bit analog-to-digital converters (ADCs) for digitizing the gyroscope outputs and three 16-bit ADCs for digitizing the accelerometer outputs.

As RFID reader, we used the ID-20LA reader module that supports ASCII, Wiegand26 and Magnetic ABA Track2 data formats. With a 2.8-5.0 volts power supply, it works on 125 kHz and it has a built-in antenna that offers a range up to 25cm using a Clamshell card.

The communication between the SmartBand and the base station is made by transceivers from Digi, called XBEE. They are using the ZigBee protocol suited for low energy consumption in applications powered by batteries. The topology of the implemented wireless sensor network is a star topology with point-to-point communication. The transceiver which is connected to the computer is set as a Coordinator. The transceiver from the SmartBand is set as an end point and sends data to the coordinator periodically. The SmartBand is equipped with the XBee XB24-Z7WIT-004 transceiver, which integrates a wire antenna. This offers an indoor range up to 30m. The Coordinator has an XBee-Pro XBP24-Z7SIT-004 transceiver with SMA antenna that increases the range up to 60m indoor.

The RedBoard is programmed to perform the tasks using the Arduino language. This is a commonly used language, merely a set of C/C++ functions that can be called from the code.

The SmartBand software runs independently from the PC application. The decisions for the right alarms are made on the SmartBand. After the initial setup stage, the SmartBand performs the steps as in the Fig. 5. If the connection to the Coordinator is interrupted, the data packet is dropped but the SmartBand operates normally.

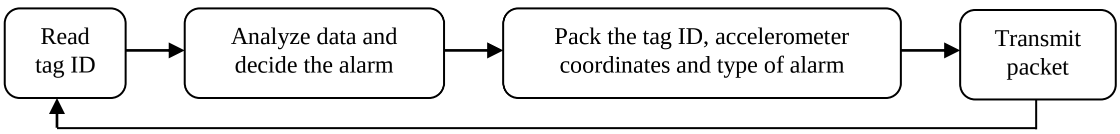

Fig. 5. SmartBand software steps

5. Prototype testing

The prototype was tested using different use cases scenarios. The results of a use case scenario execution can be visualized using the sequence of events generated by the SmartBand of a person who visit the room. This sequence is stored in a file by the application running on the PC. In the following, we exemplify the results of a use case scenario execution. We added at each line a comment explaining the meaning of the alarm.

Date: 18.02.2016

6:20:33 PM Dr. X Place: Outside Alarm: Green

6:20:53 PM Dr. X Place: Door Alarm: Orange // At 6:20:53 PM, Dr. X is at the door and the led color is orange to encourage him/her to go to the sink and sanitize his/her hands before doing any other action.

6:21:00 PM Dr. X Place: Sink Alarm: Orange //At 6:21:00 PM, Dr. X is at the sink and the led color is orange for 40 seconds to measure the hand hygiene duration.

6:21:43 PM Dr. X Place: Sink Alarm: Green //At 6:21:43 PM, Dr. X is still at the sink but the led color turned to green after completing the 40 Sec to show that Dr. X has complied with the hand hygiene protocol.

6:22:58 PM Dr. X Place: Bed 1 Alarm: Green//At 6:22:58 PM, Dr. X moved to the first patient to treat him/her with a green led color to show that his/her hands are sanitized.

6:24:27 PM Dr. X Place: Bed 2 Alarm: Orange//At 6:24:27 PM, Dr. X moved to the second patient: the led color is orange to encourage him/her to go to the sink and sanitize his/her hands before going to the second patient.

6:24:37 PM Dr. X Place: Bed 2 Alarm: Red//At 6:24:37 PM the led color turns into red: Dr. X ignored the alert.

6:24:54 PM Dr. X Place: Sink Alarm: Orange//At 6:24:54 PM Dr. X arrived at the sink.

6:25:38 PM Dr. X Place: Sink Alarm: Green//Dr. X spent 44 seconds at the sink.

6:25:48 PM Dr. X Place: Door Alarm: Green//At 6:25:48 PM Dr. X leaves the room.

6. Conclusions

This paper highlighted the HAI as a dangerous issue facing the hospitals today. Official statistics from many countries demonstrate the problem dimension and the necessity of combating the HAI. Traditional and ICT solutions used till now for preventing and combating the HAI have been reviewed.

We described a system prototype that we designed for monitoring the compliance of the hand hygiene rules in a hospital room. The system prototype has been presented in detail, including the designed wireless sensor network, with a diagram showing that the system is scalable. The communication way and the data transmission were also addressed in the paper. We described the alerting mechanism and the GUI of the application running on the PC. Also, the paper presents the architecture of the SmartBand prototype that we designed and implemented.

The designed system allows the recognition of the SmartBand holder, identifying his/her position, measuring the hand hygiene duration, reading the hands motions and presenting them on the base station in real-time, with the ability to take decisions locally and emit alerts at the appropriate times. The data gathered from the physicians/patients SmartBands are stored in files on the base station, for further analysis.

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