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Human condition monitoring in hazardous locations using pervasive RFID sensor tags and energy-efficient wireless networks

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Abstract: Tracking persons in dangerous situations as well as monitoring their physical condition, is often crucial for their safety. The systems commonly used for this purpose do not include individual monitoring or are too expensive and intrusive to be deployed in common situations. In this project, a mobile system based on energy-efficient wireless sensor networks (WSNs) and active radio frequency identification (RFID) has been developed to achieve ubiquitous positioning and monitoring of people in hazardous situations. The system designed can identify each individual, locate him/her, send data regarding their physical situation, and ascertain whether they are located in a confined space. A new algorithm called time division double beacon scheduling (TDDBS) has been implemented to increase operation time and data transmission rate of the nodes in the system. The results show that the use of this system allows us to find the location and state of a person, as well as to provide an analysis of the potential risks at each moment, in real time and in an energy-efficient way. In an emergency, the system also allows for quicker intervention, as it not only provides the location and causes of the event, but also informs about the physical condition of the individual at that moment.

Key words: Active RFID, Wireless sensor networks (WSNs), ZigBee, Human monitoring, Time division double beacon scheduling (TDDBS)
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1 Introduction

Due to a progressive increase in the age of the population, the use of systems for monitoring medical states or for housework assistance to people with reduced faculties, such as memory loss, is becoming ever more necessary. In hospitals, there is also an increasing requirement for cheap and widespread systems that would locate patients and trigger the corresponding alarm in case of an emergency. The situation is similar in places where, even though the personnel are healthy, the danger in the working environment makes them vulnerable. Positioning and monitoring of workers is crucial for companies with personnel in hazardous or high-risk locations. Safety at work has in fact become one of the biggest worries for European governments. Every year in the European Union there are 5720 fatal work-related accidents and millions of people are injured or have their health seriously harmed at their workplace (European Agency, 2000).

In this paper we are going to consider those places in which health and physical conditions of persons can be at risk, be it due to their previous physical condition or to the existence of certain mechanical, chemical, or biological agents that could cause damage. This is the case of working environments in which any minor mishap can develop into an emergency situation. An example of these is confined

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space, with limited access, unfavourable natural ventilation, and with insufficient space inside to allow for the unrestricted mobility of a human being (Veasey *et al.*, 2006). In these situations it is crucial to have in place a system for the monitoring of the physical condition of individuals (Fig. 1). Normally, workers who find themselves in dangerous places do not have a direct means of communication with the outside. In these cases it is important to know beforehand where each individual is and the circumstances that could have caused an accident and that can also put a rescue party at risk.

Fig. 1 Rescue of a worker who has suffered an accident

In this paper, the use of a system based on an energy-efficient active RFID and a wireless sensor network (WSN) is proposed with the objective of achieving the positioning and monitoring of people who find themselves in high-risk situations. The RFID part is composed of readers and active tags with sensors that collect information regarding the physical state of the person who carries them. In this system, the individual location is obtained through the identification of the active tag and the position of the antenna used to communicate with it. A ZigBee network is used to connect stand-alone mobile readers. This network of readers has an auto-routing process allowing nodes to change location and to be dynamically introduced in the network. This way, the information can reach the coordinating node from which the data is sent to the control centre, in real time and with very low power consumption.

2 WSN and active RFID applied to human monitoring

Through the use of current technology, it is nowadays possible to achieve efficient human monitoring in a number of specific situations. WSNs are already being used for monitoring human health in medical environments, carrying out measurements of light, temperature, movement, human activities, breath rate, pulse, etc. (Virone *et al.*, 2006). The use of a network of sensors at hospitals or at home also allows doctors to track the health condition of their patients. Furthermore, physical sensors can be included in the clothes of individuals to have a more direct access to their vital signs (Pandian *et al.*, 2008).

The workers, as well as the companies employing them, must always be aware of the potential risks that can exist in their working environment. It is also crucial for companies, especially for those performing activities of special risk, to have information available in real time regarding their workers, including their physical condition and their location. Currently, the available information is restricted to measurements carried out in the surrounding areas and WSN is generally acknowledged to be the best technology to guarantee access to this kind of information. This technology is already being used in cases of early forest fire detection (Bayo *et al.*, 2010), and also in the measurement of noise levels in urban environments (Santini and Vitaletti, 2007). However, in addition to this data, it is necessary to obtain information about each individual, e.g., to ascertain whether a worker remains inside a confined space or has already vacated it. Currently no automatic method exists to certify the presence of a worker inside a confined space, because it is usually not possible to establish a direct communication with him/her. This may be due to the existence of areas of controlled radiation, or those surrounded by metallic or absorbent elements which shield electromagnetic waves. To tackle this problem, a second person must be stationed outside these zones taking charge of communicating with whoever is inside, usually by cable, thereby observing the physical situation of this person at every moment. Through the technology proposed in this paper, this practice can be improved.

The active RFID technology with sensors, which we propose, is already widely used in the monitoring of special products and for the collection of data from their environment. Deicke *et al.* (2010) implemented a system to control the life-cycle of tyres as well as the pressure values and air temperature in them, using active RFID tags with sensors that communicate wirelessly with readers on the vehicle. Research into the incorporation of sensors on RFID tags has resulted in a reduction on energy consumption of these tags to lengthen their operation time (de la Fuente Ruz *et al.*, 2007). An example of an application of these tags is that found by Abarca *et al.* (2009) in which, through the use of active RFID tags, it was possible to monitor the characteristics of hemoderivate products used in hospitals, at their extraction, at storage, and at their usage. The process of fusion between RFID and WSNs, which will be used in this project for the monitoring of people, will be analysed in more detail in what follows.

The combination of RFID active tags and sensor nodes, especially when the former are provided with sensors, has led to consideration of new ways to make them interact with each other and operate together. Liu *et al.* (2008) analysed the benefits of integrating these two pieces of technology. With the use of RFID, new functions can be added to the traditional monitoring of patients in a hospital as shown in Raad (2010), since this technology allows for the identification of the patients inside as well as outside restricted areas. In the previously referenced works, RFID and WSN were used together. However, RFID is considered in the majority of cases as an element adding more information, i.e., an extra sensor, to the WSN. In some cases, the sensors are inside the RFID readers and passive tags are used to identify passing products. In others, active tags provided with sensors transfer product ID, plus additional information about the environment, to the RFID readers. In any case, the information provided by sensors is sent using a determined protocol of communications and the identification of the tag (electronic product code or EPC) is usually transmitted using the protocols defined by EPC Global (EPCGlobal, 2003). To integrate all the information into a single protocol, a communication standard based on the EPC Class1 Gen2 is being developed, which is capable of including all the information coming from any sensors that can be incorporated into active RFID tags. Along these lines, Harrop and Das (2009) introduced the concept of 'RFID EPC Generation 3'. Overlapping the growth of the mostly passive second EPC generation, active RFID technology takes new strength in this third generation. Palomo-López *et al.* (2010) incorporated their contributions to the existing protocols, based on Carrier Sense Multiple Access (CSMA), for active tags. Lopez *et al.* (2009) used active RFID technology with sensors to monitor the surrounding elements. The objective in these cases is for all the elements to be capable of transmitting not only their identity, but also information regarding their physical condition. These elements are already known as 'smart objects', and the places where they are located as 'smart environments'. The integration of RFID and WSN is apparent and, in the present paper, it can be named 'wireless sensors and RFID for smart environments' (WISSE), referring to Lopez *et al.* (2009). The objective of this project is not the development of a new protocol for a global use of active tags but rather, to find the solution to a recurring problem through the fusion of RFID and WSN in one single platform.

3 Implementation of the system

The wireless technology most widely used is, without a doubt, that of mobile phones. Nevertheless, the use of such devices is not always possible in hazardous environments, either for lack of coverage or for data capturing considerations. As an alternative, the use of WSN and RFID is proposed in this paper. In this solution, radio communication is carried out between transmission points, which form a network of routers sending and receiving information, acting as signal repeaters. These routing nodes can be deployed by workers as they enter, for instance, a cave, a pipeline, or a reservoir. The worker is tracked through a bracelet, and when he/she detects lack of signal coverage, indicated through an acoustic warning signal, he/she can step back to activate and deposit a new repeater. ZigBee is used among these repeater nodes and RF from the bracelet to the nodes. RFID allows for the unique identification of each person with an active tag, which also gathers information on the physical state of the person through a series of sensors.

Both RFID and WSN are used in the designed system in a similar way as explained in G.Escribano *et al.* (2009), where the information was collected by readers from active tags, while these readers were also acting as network nodes on the WSN. In later deployments, the system first proposed in G.Escribano *et al.* (2008) was duly refined and redesigned to match the requirements of new applications such as the handling of resources at an airport (García Ansola *et al.*, 2011).

In the new specific development proposed here, there are two levels of communication: a ZigBee wireless network and an ultra-high frequency (UHF) protocol by Texas Instruments (TI) called SimpliciTI (Fig. 2). The WSN used is based on the protocol known as ZigBee (PHY and MAC of IEEE 802.15.4). Analysing the results obtained in Lee *et al.* (2007), this protocol has been chosen for its simplicity over Wi-Fi or WiMax (IEEE 802.15.11) wireless protocols, and also for its efficiency in the transmission of data, as it consumes less resource than Bluetooth (IEEE 802.15.1) or ultra-wide band (UWB) (IEEE 802.15.3), while providing a longer range. The protocol of communication between readers and RFID tags is SimpliciTI by TI that incorporates source code for RF communication provided by this company together with the hardware that has been used for this development. As Friedman (2008) described, "SimpliciTI is a simple low-power RF network protocol aimed at small RF networks. Such networks typically contain battery operated devices which require long battery life, low data rate and low duty cycle and have a limited number of nodes talking directly to each other …".

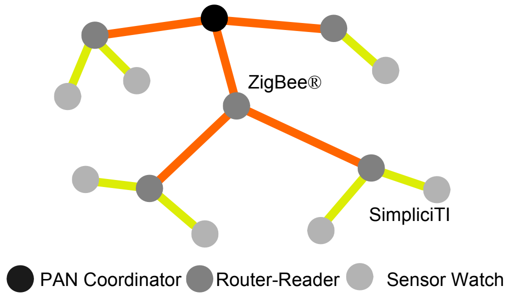


Fig. 2 Outline of communications between the different modules of the system

The ZigBee communications network is a meshed network with three types of elements: coordinators of the personal area network (PAN), routers, and end devices. To summarize, ZigBee provides dynamic networks, which work as follows: coordinators create networks and provide a network address to those who request one, be it routers or end devices. When routers enter the network, they request a network address and offer subnetwork addresses to whoever requests them. End nodes simply make requests for network addresses. Routers therefore serve as repeaters of the information arriving to them from the subnetworks towards the nodes they have above them. RFID readers can be programmed as end devices or routers. In this development they are being used only as routers, so that all RFID readers will also serve as information repeaters. In short, the physical elements that constitute the system are: PAN Coordinators, Router-Readers, and active tags (known here as Sensor Watches).

In Fig. 3 images of the different devices are shown (as they have been developed by the Autolog Group, UCLM) along with their final aspect. A diagram has been added beside each device showing how the different components are interconnected, as well as their structure and the microcontrollers that have been used.

As mentioned above, the proposed system uses an active wrist RFID tag that has been called the 'Sensor Watch'. This name has not been chosen at random, since it consists of a wristwatch which is used to individually monitor people (Fig. 3a). More precisely, the watch being used is a programmable watch with sensors, from TI, commercialised as ez430-Chronos. A specific active tag was initially developed for this purpose, but it was then replaced by this commercial device due to the following reasons:

1. The ez430-Chronos is a robust and reliable device, with a relatively low cost (35€). The material it is made from is natural resin (a harmless material to the majority of chemical reactions), and the box is watertight and waterproof up to a pressure equivalent to a depth of 30 m.

2. This watch has a CC430F6137 controller (also by TI) integrated in it, which is accessible for programming through a pluggable adapter. This microcontroller also includes a 1 GHz RF transceiver, for wireless transmission of information.

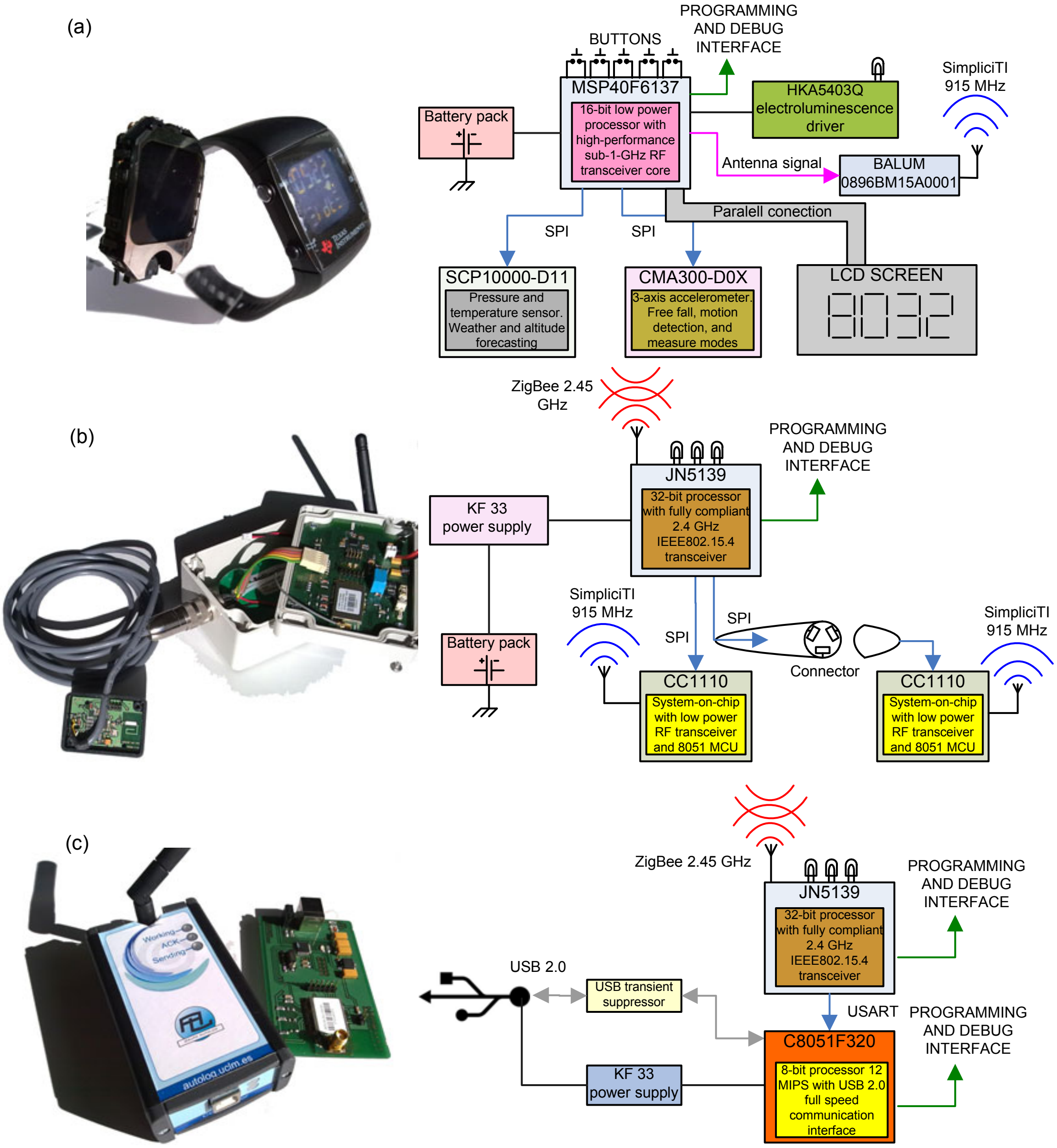


Fig. 3 Diagrams and final aspect of the devices composing the system: (a) Sensor Watch; (b) Router-Reader; (c) PAN Coordinator

3. Its evaluation kit provides a large quantity of source code, like operation or driver libraries, ready to be integrated in the new applications to be developed.

4 System operation

In this section, the operation of the developed system will be described in detail. First, there will be an explanation of how each one of the composite elements works, followed by a description of the protocol of communication between Sensor Watches and Router-Readers in more detail, as well as that between these and the nodes of the ZigBee network. Energy efficiency is especially important, at both protocols, for the application at hand to provide the longest possible operational time while running on battery power. To achieve this all elements remain in sleep mode, and become active only to check if there is new data to be processed or transmitted.

4.1 Operation of the different components

The Sensor Watch collects the data from its sensors and sends it to the closest Router-Reader. Once there, this information, along with the identification of the Sensor Watch that has collected it and that of the first Router-Reader that has read it, is transmitted through the network to the PAN Coordinator. The operation of the Sensor Watch (Fig. 4) begins with the initialisation of the system and its variables. In the diagram, three threads of independent operation can be observed, appearing after initialisation. These threads are the main program, the interruptions of the ports, and the timer. In our case the operation of the Sensor Watch is based on the collection of data from the accelerometer included in the watch. This accelerometer is used to check the activity of the worker, thus detecting lack of movement (it is rather unusual for a person not to move their hands even while in repose) or a fall (zero acceleration is also very unusual). In both cases, the device sends a message of alarm to the Router-Reader. To detect immobility, the watch compares periodically the current value measured by the accelerometers with the previous reading. In the main program thread, the normal state of the device is that of low consumption mode, and it changes into operation mode only when a Wakeup Event takes place. This event can be a button being pressed or the accelerometer detecting unusual movements.

The operation of the Router-Readers is somehow more complex as these devices incorporate two microcontrollers, CC1110 and JN5139 (Fig. 3b), where its operation is shown to be divided into two parts. Fig. 5 shows a flowchart with the functions performed by the CC1110 divided into three threads, corresponding to the main program, the ports, and the timer as in the case of the Sensor Watch. The main thread turns on the communication, waits to receive new data from the SimpliciTI, and saves them to a buffer. This communication is activated approximately every two seconds and then turned off. The interruption thread for the UART is activated when there is a data requirement from the JN5139 through this port. This thread is in charge of sending the data from the buffer to the aforementioned microcontroller.

The operation of the JN5139 is shown schematically in Fig. 6. The main program requests data only from the CC1110 through the UART port and then sends them over the ZigBee network. Once the ACK signal is received for a transmission, the node returns to sleep mode for around five seconds, a period which will later be referred to as GAP.

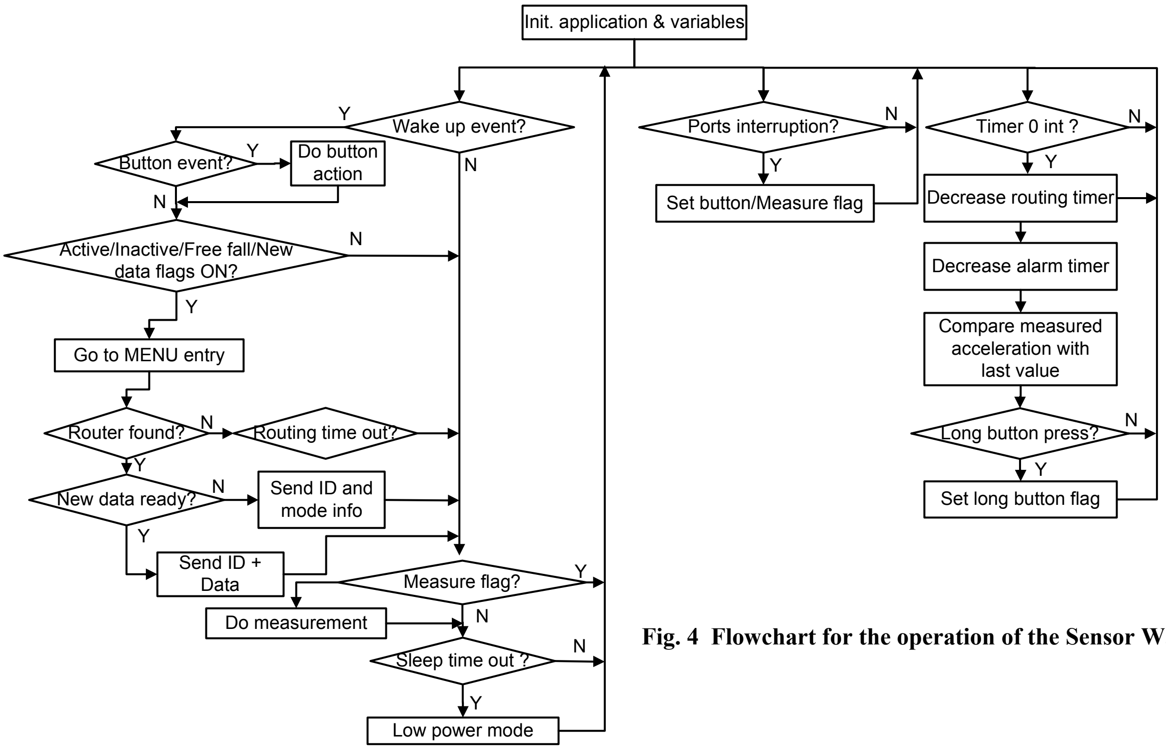


Fig. 4 Flowchart for the operation of the Sensor Watch

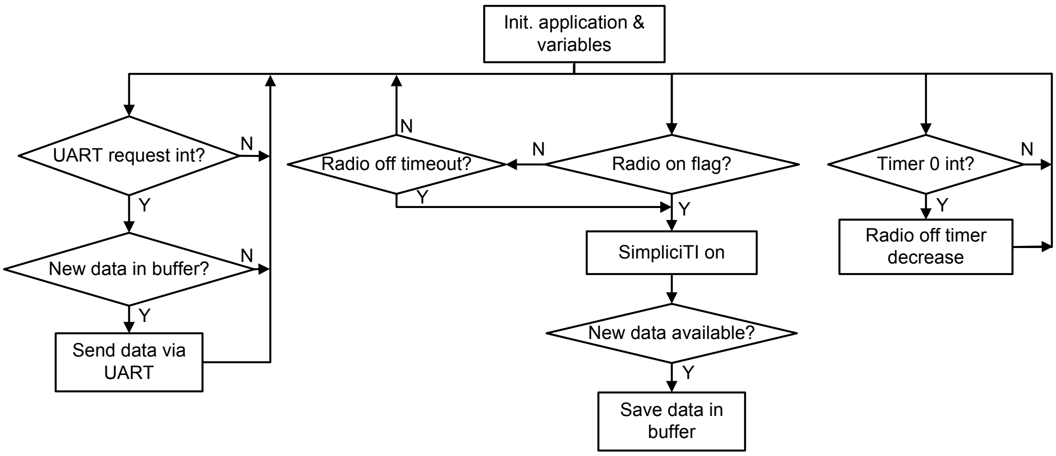
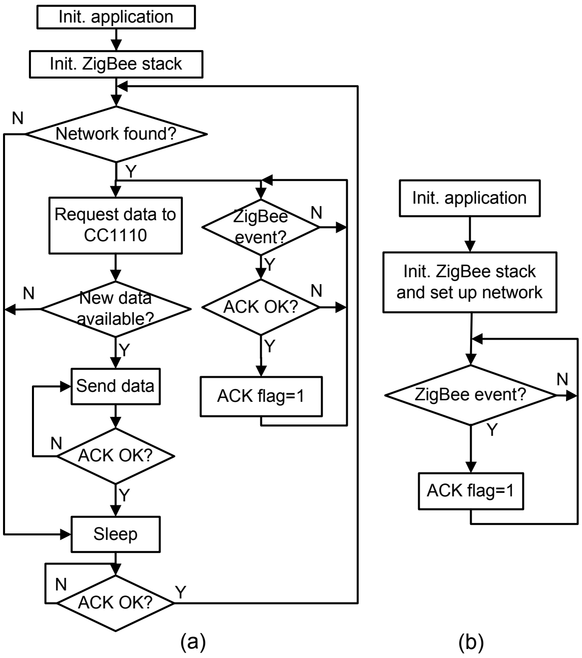


Fig. 5 Operation of the CC1110 microcontroller at the Router-Reader



(a) (b)

Fig. 6 Operation of the JN5139 microcontroller at the Router-Reader (a) and at the PAN Coordinator (b)

The PAN Coordinator operates as shown in Fig. 6b. As can be seen, the operation of this node is quite simple, since it remains alert only to receive data from the network and sends it via USB to the computer with the specific management application. As this node can always be connected to the power supply, it does not require any changes to low consumption mode.

4.2 Communication protocols used

The system uses two communication protocols: ZigBee and SimpliciTI. The reason for these choices was explained in Section 2, where their physical implementation was also described. How each of these protocols works will now be described in more detail.

ZigBee is an established protocol based on state-of-the-art R&D algorithms for the implementation of low speed ad-hoc networks. This protocol bases its lowest levels (PHY, MAC, and DLL) on the WPAN, IEEE802.15.4 standard, and therefore the data pattern sent through the network is similar, i.e., the addresses of origin and destination, frame length, data, and ACK. The modulation used is BPSK, in small frequency ranges, and QPSK in larger ones, with a maximum transmission rate of 20 and 250 kb/s, respectively. The use of CSMA/CD avoids the possibility of collisions between different nodes attempting to access the media.

The SimpliciTI protocol is used by the TI devices: the Router-Reader CC1110 and the Sensor Watch CC430F6137. This protocol uses the 906–924 MHz frequency range and a data transmission rate lower than 40 kb/s. The architecture used is simpler than those in other protocols as there are only three layers: hardware control (BSP) and radio transmission (MRFI), a network layer (NWK) managing the transmission and reception queues, and the application layer with functions such as Ping, Link, and Join among others. The NWK layer manages the ports, so that when a Link is requested, a port is assigned to the application that remains open until the network layer closes it. There are various types of devices: end devices (EDs), access points (APs), and polling devices (PDs). The network can be formed just with two EDs establishing a peer-to-peer communication, or by connecting a greater number of EDs through an AP.

The function 'Join' is used by the APs to send data to specific EDs. For our specific application the Router-Readers are APs and the Sensor Watches are EDs from the SimpliciTI network.

4.3 Time division double beacon scheduling

The reduction in energy consumption is one of the key objectives of this project, to make it possible for Sensor Watches and Router-Readers to be operated with batteries. Different protocol settings have been tested to try and achieve this aim. In the communication with SimpliciTI, the access level control to the AP is used so that should the Sensor Watch need to send a fall, immobilization, or wake-up message, this ED performs the function 'Link' without having to wait to receive data from the AP. The information corresponding to the different events can be found in the last byte of the network address of the device (Fig. 7a). Only when the user specifically requests a data transmission from all the sensors, is the protocol used in its totality, including the function 'Join', which implicates the bidirectional transfer of data using the longest frames (Fig. 7b) and therefore, high energy consumption. The reduction of energy consumption is also achieved through the reduction in the duty cycle. This way, CC1110 transceivers of the Router-Readers do not work 100% of the time; instead, they switch themselves off and on at specific intervals to check for new data. Sensor Watches only try to route and send data when a specific event takes place: a fall from a height, becoming immobile or returning to activity, or when the user requests the sending of data by pressing a button at the watch.

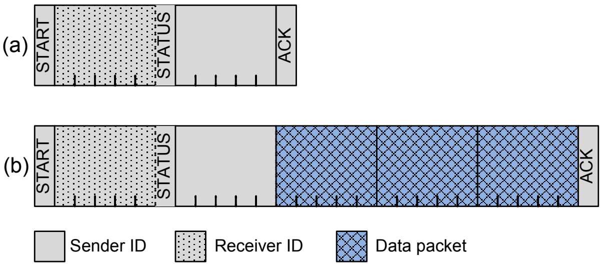


Fig. 7 Data frames used in SimpliciTI: (a) identification block and sending of the basic events frame; (b) bidirectional sending of a data frame

Most of the energy consumed by the Router-Reader devices is used in the processes of activation, routing, and sending of data via ZigBee. According to the regulations of the ZigBee protocol, the use of beacons is an available option. Nevertheless, here the beacon mode is not used, and the time division beacon scheduling (TDBS) (Koubâa *et al.*, 2008) mode has been preferred. This mode allows us to use our own 'periodic beacon frames' to switch off the devices (Fig. 8), which are reactivated after a period of time (GAP) has passed. The network tree has been used to establish a 'parent-child' configuration for the communications among routers, where parents are in charge of sending 'parent beacons' to their children (that do the same in turn acting as parents to their own children). In this setup, parents do not become inactive until all their children have finished their own operation, which in practice means that they have to send another switch-off beacon to their ancestors, i.e., a 'child beacon'. Fig. 8 shows the synchronisation process between parents and children in a network with six levels of hierarchy and a single node per level. This diagram has been called time division double beacon scheduling (TDDBS), due to the requirement of two beacons per cycle. Comparing the proposed method with the ZigBee beacon-mode (Fig. 9), we can see that the sending of a data packet from a node on the last level to the coordinator requires far more time for ZigBee than for the TDDBS.

In Fig. 8, the time in which radio communication is active in the node is shown as τ, and the minimum unit of time to carry out a reception-transmission of data is shown as u. As can be seen in Fig. 8, the process of synchronisation between the different hierarchical levels occurs at the beginning when the network is forming, and it adjusts the deactivation periods of all nodes taking into account the fact that the initial activation of each one occurs at a different instant. If one device is activated but there is no active parent, it will have to wait until it has a father before sending all its information. As can be observed in Fig. 8, in the case where only a network request is made, the time in which the different routers are switched on is much less than when all the data from the sensors also has to be sent.

4.4 Development of the firmware used at the nodes

This subsection shows the previous network models and operating schemes as they have been programmed at the corresponding microcontrollers.

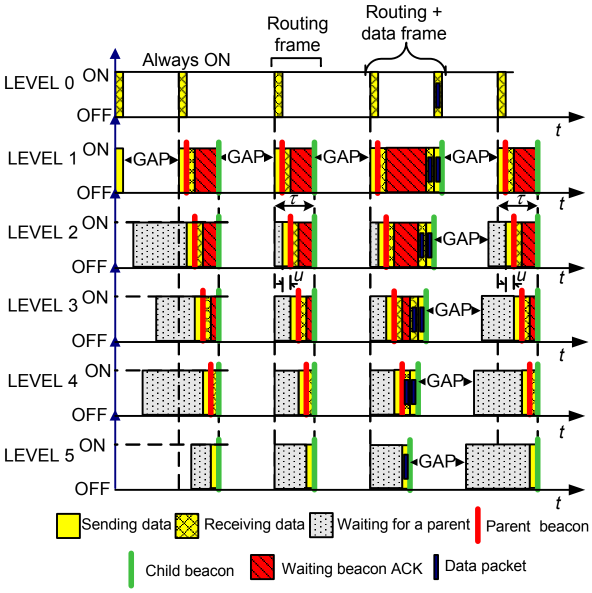


Fig. 8 Synchronisation between parents-children, in a tree network with six levels using the TDDBS beacon system

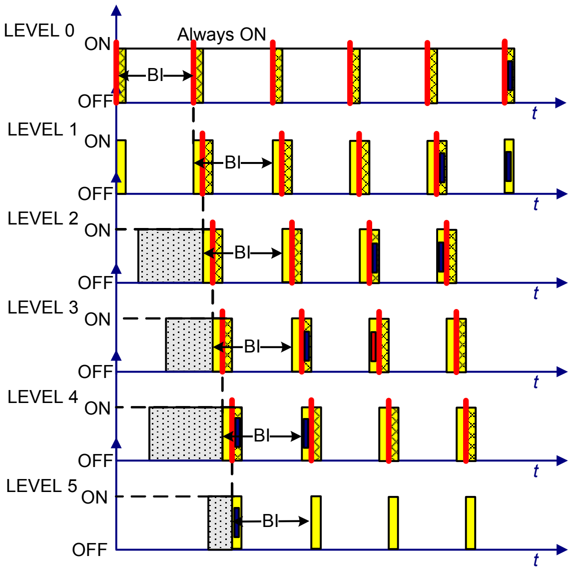


Fig. 9 Synchronisation between parents-children, in a tree network with six levels using the beacon-mode by ZigBee

The microcontrollers used are the JN5139 (incorporated at the ZigBee module) for Router-Readers and PAN Coordinator, and the MSP430F6137 microcontroller for Sensor-Watches. Firmware has been developed for the first using the Code Blocks programming tool and built over the provided ZigBee protocol stack. The second microcontroller had been originally pre-programmed with the source code corresponding to the standard application of the sports watch. This source code has been modified to comply with the required operation for this application.

The configuration and network setup are shown in Fig. 6. There are two initial steps to be performed by every node: application initialization and network configuration. After that, all routers wait for a stack data event to process transmission operations before falling into stand-by node. Functions are processed in the following order:

```
PUBLIC void vNetwork_StackMgmtEvent
    (teEventType, void *);
PUBLIC void vNetwork_StackDataEvent
    (teEventType, void *);
PUBLIC void vNetwork_HwEvent
    (uint32, uint32);
PUBLIC teJenieStatusCode  eNetwork_Tx
    (uint64, uint16, uint8 *);
PUBLIC void vNetwork_Rx
    (uint32, teJenieSleepMode);
```

The use of two antennas is a common solution for applications where there are open-space elements combined with others that have to be put into confined spaces (e.g., one antenna outside and the other inside a reservoir). Therefore, it is necessary to implement a function to take charge of antenna management. The following important operations are performed in AntennaProccessing():

```
void AntenaProcessing(void){
  switch(Status){
    case START_RF: …
    case WAIT_ACK_START: …
    case GET_IDS: …
    case WAIT_ID: …
    case GO_SLEEP: …
    case STOP_RF: …
    case WAIT_ACK_STOP: …
    case SWITCH ANTENNA: …
  }
}
```

The two instances of ‘WAIT_ACK’ are the moments in which the system waits for acknowledgement of the beacon from the child after completing the data transmission operation. This constitutes the basis of the developed TDDBS model.

4.5 Expected operation time

Knowing the operation time of a device, i.e., the time in which it can operate independently using its built-in batteries, is a main requisite in the majority of mobile systems. When it comes to calculating the operation time, a comparison between the available energy in the batteries and the power consumed by the routers has to be made. We have carried out measurements of the energy consumption using an oscilloscope in real-time of a Router-Reader (Fig. 10). As can be seen in Fig. 10, there are three levels of consumption of electricity: a minimum level of around 50 μA, another of around 22 mA, and the last level that is roughly of 68 mA. The first of these corresponds to the state of low consumption, the second corresponds to the powering of the SimpliciTI radio, and the final one corresponds to the periods of routing and sending data through the ZigBee network to the coordinator.

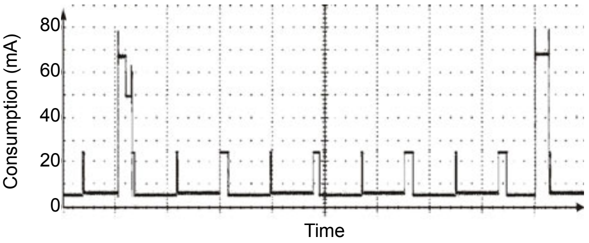


Fig. 10 Diagram showing the electric current requirements of a Router-Reader

The total energy consumed by a device will be the result of multiplying the current by the supplied tension and by the time of the operation. In the case we are concerned with, and using superimposition to calculate the total energy, the energy consumptions can be divided into different parts, each due to a different consumption level. For each level i, the total energy consumed $E_{\mathrm{T}i}$ can be obtained from the product of the total time by the average power $P_{\mathrm{AV}i}$:

$$E_{\mathrm{T}i} = P_{\mathrm{AV}i} \cdot t. \tag{1}$$

In our study, the duty cycle is going to be used instead of the total operation time. For this, we will use the definition of average power from the duty cycle, shown in Eq. (2), where p stands for the power used in a single cycle. With this, the total energy consumed by a device of n consumption levels can be expressed as E_{T}, in a period of time t, using the duty cycle of each one of in Eq. (3):

$$P_{\mathrm{AV}} = \frac{p \cdot \tau}{T} = p \cdot d_{\mathrm{C}}, \tag{2}$$

$$E_{\mathrm{T}} = \sum_{i=1}^{n} p_i \cdot d_{\mathrm{C}i} \cdot t = V \cdot t \cdot \left(\sum_{i=1}^{n} i_i \cdot d_{\mathrm{C}i} \right), \tag{3}$$

where P_{AV} is the average power consumed, T the length of the cycle, τ the period of time in which the energy level in level i is produced, V the supply tension (assuming it is constant), i_i the instant current consumed in level i, and $d_{\mathrm{C}i}$ the duty cycle for level i.

4.5.1 Consumption level for the ZigBee duty cycle

The duty cycle of a device corresponds with the time in which it remains switched on. The consumption level τ_{Z} for the ZigBee duty cycle depends on the following parameters (Fig. 8): the number of hierarchical levels in the network, the number of children that each node has and whether the devices act only as routers or if they also send information from sensors to superior levels. Fig. 8 shows how those nodes that switch off have to wait until their ancestors are active in order to be able to start transmitting again. This waiting time (usually measured in ms) is the time between switching off of the node and the next activation of the parent node. That is to say, in a synchronised network, all the devices have an identical τ. Therefore, to estimate the consumption of the nodes we have to calculate that value.

First, the duration of the necessary period of the routing (τ_{r}) has to be calculated. The routing period of a tree network like that in Fig. 11, must be enough for all the branches of the first level to be routed among them along with their children and respective descendants. When the first child is routed, its descendants follow suit, and so on, until the tree is completed. Using the node numbering system in Fig. 11 ($R_{jklm\ldots}$), the time spent in routing the entire network will be the time needed by the last node which routes, that is, the one in which all its indices add up to the maximum value, according to Eq. (4):

$$\tau_{\mathrm{r}} = \max(\tau R_{jklm\ldots}), \tag{4}$$

where $\tau R_{jklm} = u \cdot (j + k + l + m + \ldots)$.

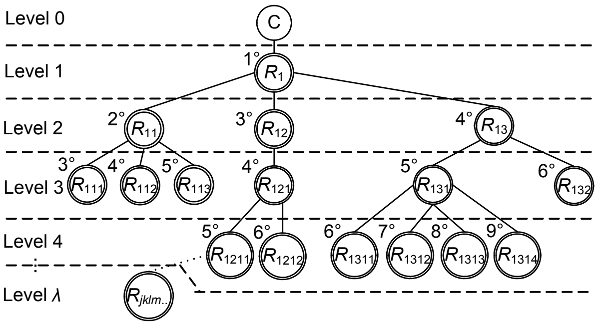


Fig. 11 Sequence of routing of a tree network with four hierarchical levels

The period for the cases where there are routing and data transmission, denoted as τ_d, can now be calculated. Observing Figs. 8 and 11 once more, we see that the duration of routing is identical to that in the previous case, and therefore we can calculate it using Eq. (4). The duration of the sending of data is obtained with Eq. (5), where λ is the hierarchical order in the network where the device is found.

$$\tau_{\mathrm{d}} = \max(\tau R_{jklm}) + \lambda \cdot u. \tag{5}$$

Finally, the energy consumption level for the ZigBee duty cycle for ZigBee communication, d_{cZ}, is obtained using Eq. (6). Two weights (ω_{r}, ω_{d}) are used here to carry out a weighted mean and take into account the fact that cycles with sending of data are generally much less frequent than those in which only routing occurs.

$$\tau_{\mathrm{Z}} = \omega_{\mathrm{r}} \cdot \tau_{\mathrm{r}} + \omega_{\mathrm{d}} \cdot \tau_{\mathrm{d}},$$

$$d_{\mathrm{CZ}} = \frac{\tau_{\mathrm{Z}}}{T_{\mathrm{z}}} = \frac{\omega_{\mathrm{r}} \max(\tau R_{jklm}) + \omega_{\mathrm{d}}(\max(\tau R_{jklm}) + \lambda u)}{T_{\mathrm{z}}}. \tag{6}$$

4.5.2 Example of operation time calculation

The calculation of the duty cycle for the actual levels of energy consumption has not yet been approached here. The last expression makes it possible to estimate the operation time of a Router-Reader. This will now be used to analyse the network in the example of Fig. 11. The SimpliciTI network has a routing process similar to ZigBee and, therefore, the calculation of the duty cycle is also similar. The SimpliciTI network (S) we are using as an example has just two levels (0 and 1), with two devices in each one. The period of low energy consumption (L) is the part of the duty cycle excluding the time used for communication for the device in the example of Fig. 10. The parameters used for the calculation are obtained from the architecture and configurations of the networks mentioned.

V=3.3 V, i_{Z}=68 mA, i_{S}=22 mA, i_{L}=0.05 mA, E_{T}= 1.2 V×3 batteries (2650 mA·h in series)=9540 mW·h.

Now the different duty cycles can be calculated. For the ZigBee network,

$$t_{\mathrm{offZ}}=16\ \mathrm{s},\ \tau_{\mathrm{rZ}}=0.5\ \mathrm{s},\ \lambda=4,\ \omega_{\mathrm{rZ}}=0.95,\ \omega_{\mathrm{dZ}}=0.05,$$

$$u_{\mathrm{Z}} = \frac{\tau_{\mathrm{rZ}}}{\max(j+k+l+m)} = 0.5/8 = 0.0625,$$

$$d_{\mathrm{CZ}} = \frac{\tau_{\mathrm{Z}}}{T_{\mathrm{S}}} = \frac{0.95 \times 0.5 + 0.05 \times (0.5 + 0.25)}{16.5125} = 0.031.$$

For the SimpliciTI network,

$$t_{\mathrm{offS}}=2\ \mathrm{s},\ \tau_{\mathrm{rS}}=0.04\ \mathrm{s},\ \lambda=1,\ \omega_{\mathrm{rS}}=0.5,\ \omega_{\mathrm{dS}}=0.5,$$

$$u_{\mathrm{S}} = \frac{\tau_{\mathrm{rS}}}{\max(j)} = 0.04/2 = 0.02,$$

$$d_{\mathrm{CST}} = \frac{\tau_{\mathrm{S}}}{T_{\mathrm{S}}} = \frac{0.5 \times 0.04 + 0.5 \times (0.04 + 0.02)}{2.05} = 0.024.$$

For the low consumption state,

$$d_{\mathrm{CS}}=1-0.031-0.024=0.945.$$

In this way life expectancy is obtained for a device in this network:

$$t = \frac{E_{\mathrm{T}}}{V\left(\sum_{i=1}^{n} i_i \cdot d_{\mathrm{C}i}\right)} = 1076\ \mathrm{h} \cong 1.5\ \mathrm{months}.$$

5 Results from the application of the system to a real environment

In this section, the results of the system in use are shown from their implementation in a real physical environment. The use of real locations for pilot testing makes it possible for the comparison of the theoretical results with those obtained in the experiment, allowing an analysis of the benefits of the proposed system over other existing technology.

Tests were carried out at an oil refining company close to our university. The specific environment consisted of a set of metallic reservoirs to store fuel. Workers had to enter empty reservoirs to perform maintenance and cleaning operations while wearing Sensor Watches. The PAN Coordinator node was connected to a management computer while Router-Reader nodes were attached to the outside of every reservoir (Fig. 12). The use of elements inside these metallic reservoirs was also necessary to maintain communication with the watches. These elements include the RF readers and antennas connected by cable to the outside Router-Reader (Fig. 3b). These modules inside the reservoirs contain another CC1110 transceiver, like the one used at the Router-Readers.

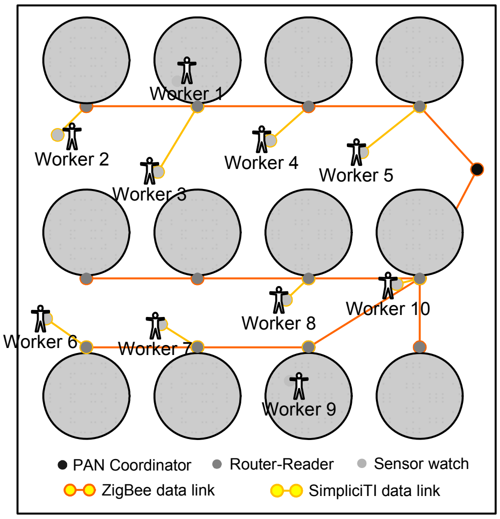


Fig. 12 Layout of the system in the application for metallic fuel reservoirs

The results obtained were quite satisfactory. A real-time position tracking of the workers was achieved, inside as well as outside the reservoirs, and the system can also trigger alarms when emergency situations occurred. The behaviour tests and measurements carried out have made it possible to obtain quantitative results in terms of effectiveness and access to the target space. Fig. 13 shows the time required to route nodes (point to point). These values have been obtained by comparing the power consumption at the nodes against the strength of the resulting signal at different distances (Fig. 14).

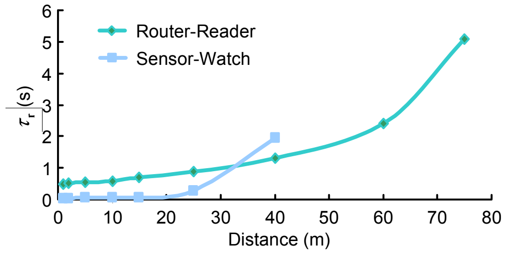


Fig. 13 Time consumed for the routing of the nodes as a function of distance to the antenna

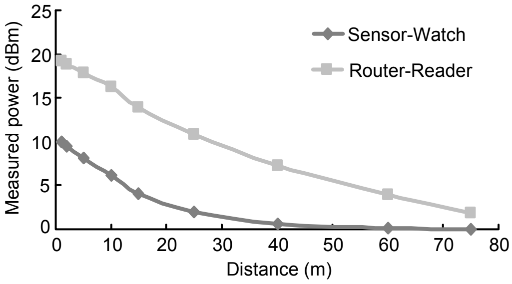


Fig. 14 Power emitted by the nodes as a function of the distance to the antenna

The system that has been designed is versatile enough to be used in other hazardous environments. An example would be the tracking of patients in hospitals to monitor their health. Of course there are other reliable systems, but ours is more simple, less intrusive, and less expensive, so it can be deployed to more patients and not just to those at more direct risk. A pilot test was made at the national hospital for paraplegics located in our area. For these patients, especially for newly disabled people who have not yet been used to their situation, it is deemed essential to keep track of their location in order to be able to identify the risks they are subject to, as well as to monitor their performance when rehabilitation activities are being carried out. Taking the characteristics of the building into account, a ZigBee network made up of Router-Readers was placed in corridors and rooms, and various PAN Coordinators can bring the information together before sending it to the control centers (Fig. 15). Each patient was given a Sensor Watch to wear whenever instructed to do so by the doctor. The behaviour, efficiency, and range characteristics of the system inside the hospital building were more important for this application than lifetime of nodes. Still, as the nodes are inexpensive and the network is dynamic, coverage and life-time issues were easily tackled by adding extra nodes at specific locations as required.

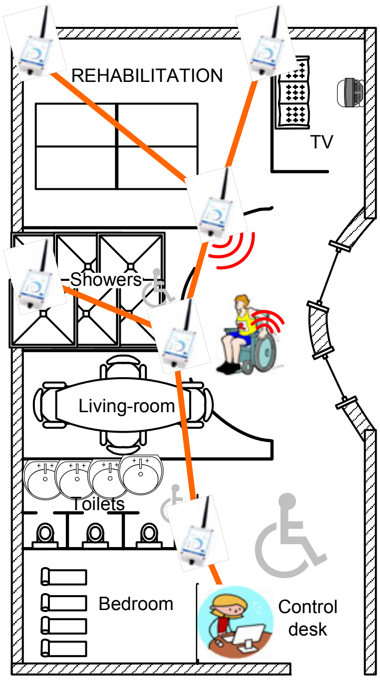


Fig. 15 Elements of the system in different parts of one hospital floor

The operation times of Router-Readers and the Sensor Watches have been analysed in the test cases above for comparison with the results obtained in Section 4. Figs. 16 and 17 show how the total number of nodes used by the network and the quantity of Sensor Watches that transmit to a same router affect the operation time of the Router-Readers.

To further justify the technology options chosen for our system, a comparison is made below between the proposed communication model, the TDDBS, the beacon-mode model in the ZigBee protocol and the classic mode in which beacons are not used. Other analysis of ZigBee routing performance in terms of end-to-end delay and energy consumption, as revised in the literature, has also been taken into account. Nefzi and Song (2007) evaluated the use of ad-hoc on-demand distance vector (AODV) versus hierarchical tree routing (HTR). Results show that tree architecture is faster but requires more energy. A revision of existing methodologies for WSN to conform to MAC routing was presented in Perillo and Heinzelman (2004). TDDBS can be catalogued in that context as a timeout-MAC method, where transmission follows a temporal stand-by period of the nodes.

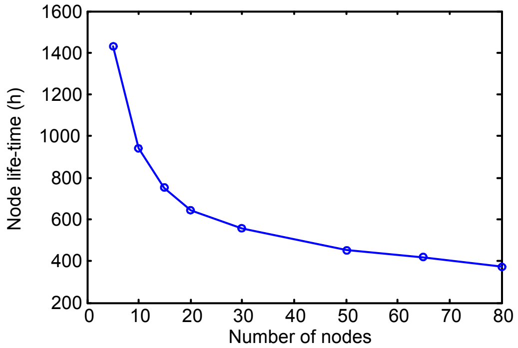


Fig. 16 Relationship between the number of nodes used in the network and the duration of the batteries (battery life) for Router-Readers

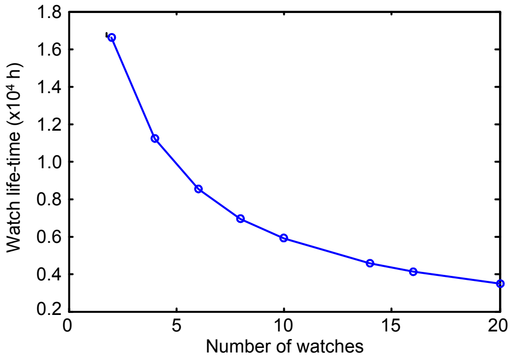


Fig. 17 Relationship between the number of nodes used in the network and the duration of the batteries (battery life) for Sensor Watches

Regarding energy consumption, it can be seen in Fig. 18 that the TDDBS system has a medium consumption (life-time) between the elevated consumption in normal mode, and the very low consumption in beacon-mode. This is due to the fact that, according to what has been seen before, for the beacon-mode the period of routing (τ_r) is proportional to the number of children and siblings that a node has, and therefore is not a fixed value for all nodes (Fig. 8). Nevertheless, the differences between these systems, also regarding energy consumption, lie in the efficiency of communication. For the case of ZigBee beacon-mode, there is no rising synchronisation between the children and the parents of the network, and therefore the moment at which data is sent occurs only in those cycles in which the children have been switched on at the same time as the parents. For example, if a child in the fourth hierarchical level has data to send, it will not do so until its ancestor is available, and at times this does not occur until the following cycle. Once the information is uploaded to its ancestor, this node may have to wait until the following cycle before sending the information to its parent, and so on. Therefore, in this case the time needed for sending a data packet using ZigBee beacon-mode is four cycles, while using the TDDBS the whole process can take place within the same cycle. Fig. 19 shows the data rate obtained in sending data using the different schemes; it can be appreciated in that the proposed TDDBS model is more energy-efficient than any of the ZigBee modes.

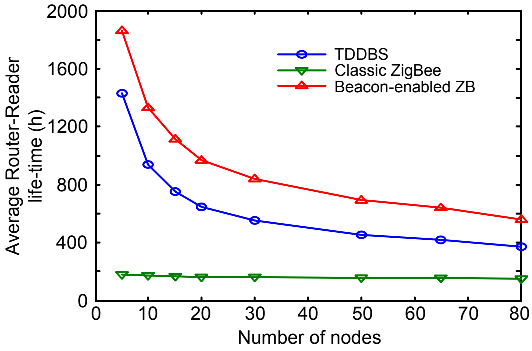


Fig. 18 Comparison of life-time between the TDDBS system and classic and beacon-enabled ZigBee modes

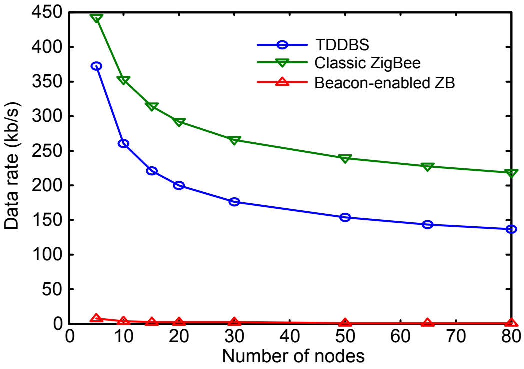


Fig. 19 Comparison between the TDDBS system and classic and beacon-enabled ZigBee modes in terms of data transmission efficiency

6 Conclusions and future work

In this paper, the development of a system for the positioning and monitoring of the conditions of people who work in hazardous and special environments has been presented. The objective of these applications is the identification, positioning, and transmission of data regarding each individual to the corresponding control stations. The system can also detect emergency situations such as falls or loss of consciousness and using this information to trigger the corresponding alarms.

The system uses two wireless communication networks: one with a very low consumption and a low rate of data transmission based on the SimpliciTI protocol by TI, and the other (with a higher consumption and read range) based on ZigBee. The final system deployed into a real environment consists of three types of elements: the PAN Coordinators, the Router-Readers, and the Sensor Watches. The PAN Coordinators are in charge of forming the ZigBee network with a long range, and the Router-Readers communicate the sensitized wrist-band with the network using the SimpliciTI protocol. In this work we have used the sensors already implemented in the commercial Sensor Watches (accelometers, pressure sensors, etc.) to monitor the physical conditions of the workers and set off the corresponding alarms in emergency situations.

Furthermore, an energy-efficient communication model that we have called TDDBS has been designed and implemented. This model is similar to the beacon-enabled mode proposed in the ZigBee protocol, but in this case we have added the use of a turn-off beacon, which is sent from the 'youngest' parent in the network, when the parent has finished carrying out all the necessary network responsibilities. In this way we have managed to synchronise all the nodes in the network when sending and receiving data, and energy consumption is thus reduced and distributed among all of them. Our model has a higher level of energy consumption than that provided by the beacon-mode proposed in ZigBee; however, it ensures a real-time communication regardless of the size of the network.

As can be observed in Fig. 18, the life-time of our TDDBS nodes is slightly shorter than that of nodes with beacon-enabled ZigBee. Nevertheless, as can be seen in Fig. 19, those nodes with the best performance in terms of battery requirements are the worse when evaluating their data transmission efficiency. TDDBS nodes, however, show an interesting compromise between efficiency in data transmission and life-time. In conclusion, our proposed method provides a more efficient system in terms of energy while still making possible real-time data transmission. Therefore, our system provides a more adequate overall solution to set up autonomous and mobile systems.

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