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IoT Heterogeneous Mesh Network Deployment for Human-in-the-Loop Challenges Towards a Social and Sustainable Industry 4.0

CELIA GARRIDO-HIDALGO[1], DIEGO HORTELANO[1], LUIS RODA-SANCHEZ[1], TERESA OLIVARES[2], M. CARMEN RUIZ[2], AND VICENTE LOPEZ[1]

[1]Albacete Research Institute of Informatics, 02071 Albacete, Spain

[2]Computer Systems Department, Escuela Superior de Ingeniera Informtica de Albacete, University of Castilla-La Mancha, 02071 Albacete, Spain

Corresponding author: Diego Hortelano (diego.hortelano@uclm.es)

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ABSTRACT This paper encourages the cooperation of different Internet of Things technologies in industrial environments for avoiding social disruption in novel Industry 4.0 paradigms. For this, green I3A smart factory (GreenISF) scenario is presented, where the deployment of a collaborative mesh network based on Bluetooth low energy (BLE) and long range wide-area network (LoRaWAN) technologies promotes human–machine collaboration towards socially sustainable factories. In order to encourage human-centric architectures in such environments, our smart wristband prototype OperaBLE is introduced in this paper as key enabler for human-in-the-loop systems. Thus, the network deployed in GreenISF is composed of body area networks which monitor labor activity and reinforce security at work by embedding sensors in regulatory industrial clothes. These networks cooperate with our BLE mesh infrastructure aimed to fulfill the major challenges Industry 4.0: zero fails, total coverage, and sustainability. Furthermore, a context information network based on LoRaWAN complements our mesh network to provide the system with valuable environmental data and prevent operators from harmful workplaces. The system is connected to a fog server responsible for preprocessing raw data that will be stored in a global cloud server. The experiments carried out highlight the contribution of OperaBLE towards safer working conditions and a sustainable digitalization of Industry 4.0.

INDEX TERMS Industry 4.0, IoT, BLE mesh, LoRaWAN, body area network, OperaBLE.

I. INTRODUCTION

Industry 4.0 represents the Fourth Industrial Revolution and can be defined as the integration of complex physical machinery and devices with connected sensors and software used to predict, control and plan for improving business and societal outcomes [1]. The five major features of Industry 4.0 are digitization, optimization and customized production, automation and adaptation, Human-Machine Interaction (HMI), value-added services and businesses with automatic data exchange and communication. These features are not only closely related to Internet technologies and advanced algorithms, but they also indicate that Industry 4.0 is an industrial process of value adding and knowledge management [2]. Mobile and cloud computing, big data, and the Internet of Things (IoT) are key-enabler technologies towards Industry 4.0 (matching with the *Manufacturing* area of the Industrial Internet [1]) that permit the establishment of smart factories, products and services. Moreover, Industry 4.0 holds a great opportunity for creating sustainable industrial value in the three sustainability dimensions: economic, social and environmental [3].

The origin of Low-Power Wide-Area Networks (LPWAN) sets the beginning of a new era where a greener IoT is encouraged for avoiding environmental disruption. These networks are being increasingly demanded due to their long range, low power consumption and robustness. In this work, firstly, we aim to achieve sustainable manufacturing. For this purpose, we use efficient algorithms, low power communication standards, sensors and actuators to permit the factory environmental management. Secondly, we take into account the human being for digitalization challenges, the so-called Operator 4.0 which are understood as a smart and skilled operator who performs not only cooperative work with robots but also work aided by machines as and if needed by means of human Cyber-Physical Systems (CPS), advanced human-machine interaction technologies and adaptive automation towards achieving human-automation symbiosis work systems [4]. Thirdly, we face the IoT challenges to reach a global standardization for permitting communication among heterogeneous devices connected to the Internet, reason why a networking scheme is presented in this work, where different technologies coexist and cooperate together.

Considering the essential requirements of wireless technologies towards Industry 4.0 (long range, large coverage, high reliability, high bandwidth, real-time operation and negligible energy impact [5] and [6]), a unique technology cannot satisfy all of them. Thus, this research not only fulfills these requirements for building a wireless global infrastructure but also focuses on workers as a part of the whole collaborative system. Particularly, this work advocates a real collaborative mesh network deployed in the so-called GreenISF, where a perfect matching between BLE [7] and LoRaWAN technologies [8] promotes social integration of workers and security at work. This network aims to provide a background infrastructure for monitoring labor activity and, thus, test how workers get involved with collaborative learning by gesture-based wearables and user-friendly interfaces.

GreenISF scenario is introduced in this paper to provide a general overview of the indoor area considered for carrying out the experiments. This scenario includes a network composed of different sub-networks including WearBANs (Wearable Body Area Networks) which are defined as dynamic due to their deployment in industrial regulatory clothes worn by operators. These WearBANs are part of a global collaborative BLE mesh network statically deployed in GreenISF and connected to a local fog controller. Furthermore, the scenario includes a LoRaWAN sub-network able to gather information of the whole environment which is conceived as the context information network that surrounds workers and monitors relevant ambient parameters. Data collected from sensors deployed in GreenISF is pretreated in a local fog server and, eventually, sent to ThingSpeak [9], a global IoT data analytics platform. Thus, a detailed report of laboractivity in the factory as well as context information is stored, being available for consults at any time. Moreover, since supervisors are expected to monitor labor activity in shop floor processes, this work includes the development of a native Android application which directly communicates with BLE mesh network to receive relevant activity reports, working conditions of operators and context information.

This paper is structured as follows: Section II highlights the related works and compares them with the main functional areas of our system; Section III describes the material and methods, as the hardware and standards used, the scenario description, the OperaBLE device, the BLE Mesh Network, the context information network and the fog and cloud computing implemented; Section IV shows the results and discussion by describing different experiments and finally, Section V concludes the paper and proposes future works.

II. RELATED WORKS

Numerous researchers are combining efforts to contribute towards an emergent knowledge area focused on Industry 4.0 by means of relevant surveys and theoretical studies [2], [10]. Many authors highlight the necessity of standardization for new technologies in order to improve significantly existing industrial systems, encouraging the adoption of LPWAN in industrial environments as primary solution [11]. However, none of them are usually based on practical analyses or case studies which provide significant data to support the suitability of such solutions.

Currently, there are no published research articles that address from a practical perspective the social and sustainable dimension of the Industry 4.0 using heterogeneous networks. Indeed, this is one of the major contributions of this paper, which provides an in-depth case study based on real experiments. In order to compare the proposed system to existing ones, the following lines highlight relevant literature related to specific functional parts of our deployment, namely: WearBAN based on industry-oriented wearable technology, BLE Mesh network communication and LoRaWAN-based industrial networks.

Our WearBAN proposal can be divided into two principal functional areas: human care and HMI. Regarding the first area, H. Thapliyal et al. show different devices which are used to detect stress [12]. They are based on some parameters such as heart rate, accelerometers or respiration sensors to achieve this aim. The majority of these devices use heart rate measurements to estimate stress. However, none of them are usually applied to industrial scenarios. In this research we propose an adaptive algorithm to identify fatigue considering energy consumption management as one of the main challenges for wearables.

Our proposal is additionally focused on movement recognition, which implies several benefits from the point of view of HMI. As can be seen in [13], thanks to an improved interaction with machines, workers could face different challenges such as flexible manufacturing and inter-disciplinary understanding, while the existing expertise gap among them could be reduced. Furthermore, in terms of movement characterization, in [14]–[16] the authors use accelerometers applied to older adults to detect declining balance, common activities and even the age of the user. Nonetheless, the use of these devices is not widely extended in industrial environments. Compared to these works, the algorithms introduced in this paper stand out because of their low-frequency operation. This contributes towards the sustainability challenge [17] and improves existing systems by permitting the recording of new movements.

The second functional area of our work focuses on BLE mesh network. Several authors use master-slave connections to allow data forwarding [18], [19], while others create mesh networks using BLE broadcast capability [20], [21].

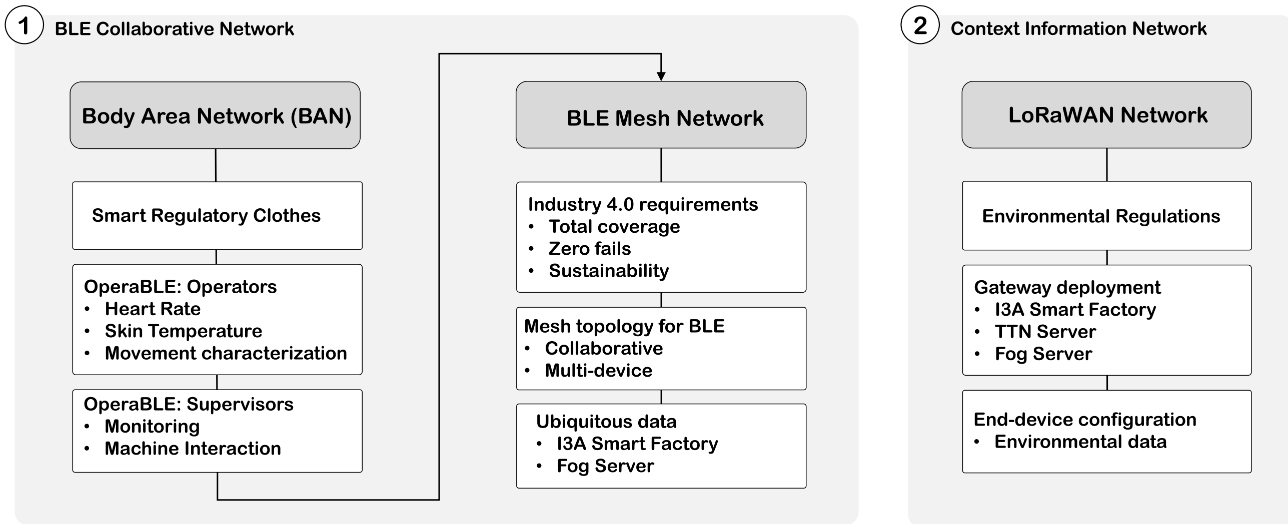


FIGURE 1. Networks deployed in our GreenIS Factory.

However, the presented works have a generic use. In [22], a BLE mesh based on master-slave connections is proposed for the Industry 4.0, but it is only focused on the real time requirement. Our mesh proposal aims to fulfill most requirements of the Industry 4.0, using broadcast transmissions, in a similar way to the posterior release of the official BLE Mesh standard [23], based on Bluetooth 5.0 version.

The adoption of LPWAN in industrial environments has grown exponentially in the last months, being LoRa and Sigfox [24] the most extended solutions. Many authors [11], [25] define them as key-enablers for the evolution of Industry 4.0, providing in-depth theoretical studies of their specifications. However, given the recent adoption of these technologies, no experimental data is usually provided to support the applicability of LPWAN standards to industrial scenarios where more than one wireless network may coexist. Although S. Penkov et al. propose the combination of LoRaWAN with the MQTT protocol applied to industrial measurements [26], no real data apart from coverage measurements are shown or analyzed during the case study. Even in the context of human care, some approaches describe test-beds where LoRaWAN would be used as an e-Health communication technology for non-industrial scenarios [27]. Nonetheless, no real data is provided to support the suitability of this technology to improve human well-being.

On the whole, although numerous studies conduct specific test-beds to evaluate individually BLE and LoRaWAN technologies, none of them consider the coexistence of both standards in industrial scenarios based on real measurements. Given the exponential growth of the Industrial Internet, the cooperation of different technologies in heterogeneous networks is an issue that must be addressed and, in view of the rapid development of Industry 4.0, social sustainability is undoubtedly one of the most challenging goals.

III. MATERIAL AND METHODS

Since the global system presented in this paper is referred to as an heterogeneous mesh network for improving social sustainability and facing an inclusiveness challenge at work, most materials consist of development boards compatible with different IoT standards. Thus, Section III-A provides an overview of BLE and LoRaWAN technologies according to their major contributions and limitations towards sustainable goals in Industry 4.0 scenarios. Figure 1 shows the networks deployed in our factory, with their main characteristics.

Two main networks can be distinguished: a BLE collaborative network and a context information network. Inside the BLE Mesh network we have a BAN which includes our wearable prototype, OperaBLE, a device where different sensors and actuators collaborate towards security and comfort of workers permitting supervisors to monitor shop floor areas. This prototype has been selected as one of the five finalist projects in the international innovation awards "Imagine Blue Awards" launched by Bluetooth SIG. The context information network consists of a LoRaWAN module for environmental monitoring.

GreenIS Factory is introduced in this paper with the objective of providing a real background to the experiments and tests carried out to verify the performance of different subsystems defined in the network. The building consists of several separated sectors that are described in detail in Section III-B, where the location for static nodes in the network and the relative position of operators and supervisors are established. Sections III-C, and III-D present our own protocol for a BLE-based mesh network encouraging collaboration between humans and machines with gesture-based worker assistance. Due to the introduction of IoT context networks in shop floor areas using LoRaWAN (which is afforded in Section III-E) security at work is ensured, being the entire system governed by a local fog server and global cloud infrastructure, presented in Section III-F.

TABLE 1. Development boards, radio modules and sensors for the GreenIS Factory.

Hardware	Functionality	Symbol	Quantity
Arduino UNO R3 [28]	LoRaWAN end-device		1
BLE112 [29]	BLE 4.0 radio		2
CSRmesh 1010 [30]	BLE mesh node		1
DHT-22 [31]	Temperature Humidity		2
FlexiForce [32]	Pressure		2
iC880A [33]	LoRaWAN concentrator		1
IMU-10DOF [34]	Acceleration		2
KY-038 [35]	Noise		2
LDR	Luminosity		2
LightBlue Bean [36]	OperaBLE wearable		4
MQ-7 [37]	Gas (CO)		2
Raspberry Pi 2 B [38]	LoRaWAN gateway		2
RN2438 [39]	LoRaWAN radio		1
SEN-11574 [40]	Pulse		1
Waspmote v2.3 [41]	BLE machine node		2

A. HARDWARE AND STANDARDS

This section details the hardware material used to set up the heterogeneous mesh proposal in our GreenIS Factory where the platforms used to carry out the experiments from Section IV are introduced. Table 1 shows a summary of the hardware selected for performing communication in our prototype, expanded during this section according to the role each platform plays in the network.

These materials have been classified in three categories according to their radio standard and role in the global network: BAN, BLE Mesh and LoRaWAN Context Information Network. The following sections provide a brief introduction to BLE and LoRaWAN standards and main devices for adding a theoretical background to the decisions taken on material selection.

1) BLUETOOTH LOW ENERGY

BLE is included in Bluetooth standard since Bluetooth 4.0 specification [7] and it defines two different network topologies for transmitting data: *connection* and *broadcast*. Due to their characteristics, each topology is appropriate to determine use cases with different strengths and weaknesses. Later BLE versions (4.1 [42], 4.2 [43] and 5.0 [44]) maintain these topologies and improve them, allowing the combination of different roles. However, these last improved versions are not implemented in most IoT devices. The available topologies available in BLE standard are explained below:

- *Connection* topology: two BLE devices can establish a connection to exchange data, permanent and periodically. Two roles are used in this topology: *master* (also called central) and *slave* (or peripheral). A *master* device can be connected with up 8 *slave* devices in a star-topology (see Figure 2a). This topology allows the data flow in both directions. Moreover, *slave* devices provide notification and indication characteristics, to send data to master in the moment they change.
- *Broadcast* topology: a BLE device can use *advertisement* packets to transmit data to any BLE device in *scanning* mode located within its coverage range. Two roles are defined in this topology: *broadcaster* (which transmits data) and *observer* (which receives data). Due to the nature of this topology, data exchange is unidirectional, from a *broadcaster* to one or more *observers* (see Figure 2b).

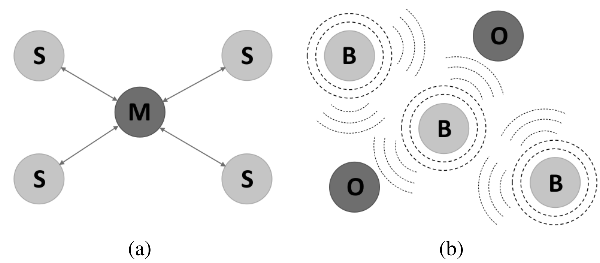


FIGURE 2. Available topologies in BLE standard (version 4.0). (a) Connection topology: (M) Master; (S) Slave. (b) Broadcast topology: (B) Broadcaster; (O) Observer.

Recently, mesh topology has been included in the Bluetooth Specification [23], although the number of real devices which implement it is very limited. In addition, there are some projects which implement this topology over BLE [45], [46], but these implementations do not fulfill completely the Industry 4.0 requirements: reliability, total coverage and sustainability [47]. For this reason, we have developed a new mesh topology, build over BLE, closer to these objectives. Our mesh topology is based on the exchange of advertisement packets, using broadcaster and observer roles, and it is exposed briefly in Section III-D. To a more detailed explanation, see [48].

Several devices have been used to develop our prototype of wearable OperaBLE for industry operators. Regarding the materials used (described in Table 1), the controller board is LightBlue Bean, which can be seen in Figure 3 (A). This device is suitable for the objective of our prototype because of the integration of BLE module into the board because of the communication technology used to transmit information. The BLE module included in this board is called LBM313 [49]. It includes I2C and SPI interfaces and several I/O pins. This board is additionally composed of RGB LED, temperature sensor, a three-axis accelerometer BMA250 [50], and a breadboard for connecting other devices. All these parts are managed by an Arduino-compatible microcontroller that has a working frequency of 8 MHz.

Although LightBlue Bean has a three-axis accelerometer, we decided to assembly another one to this device for future studies, it is called IMU 10-DOF (see Figure 3 (B)). It has ten degrees of freedom thanks to its sensors, these are:

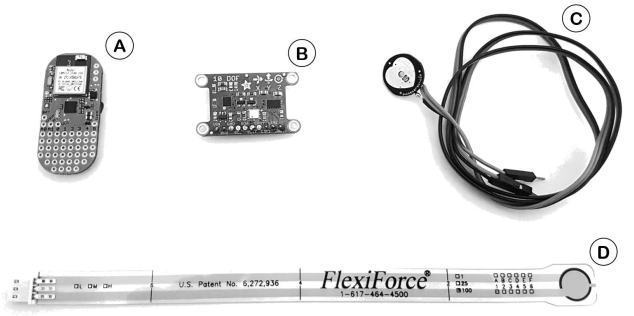
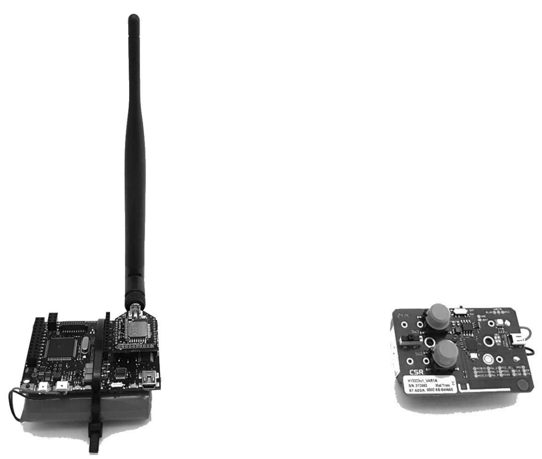


FIGURE 3. **Body Area Network devices. A: LightBlue Bean, B: IMU 10-DOF, C: PulseSensor, D: FlexiForce.**

a three-axis gyroscope, a three-axis accelerometer, and a three-axis magnetometer and pressure sensor. The sensor that has been used in this paper is the accelerometer LSM303DLHC [51]. Its sensitivity is adjustable within four different ranges, which communicates via I2C with LightBlue Bean. Moreover, Figures 3 (C) and (D) include the heart rate sensor [52] and the pressure sensor [53] used for the experiments, respectively.

Regarding the BLE mesh topology development, the hardware platforms used in our studies are Waspmote devices (see Figure 4a) from Libelium [54], using a BLE radio module equipped with BLE112 chipset from BlueGiga [55] and CSR1010 devices [30] (see Figure 4b) from CSR [56], equipped with a BLE 4.1 radio.



(a) (b)

FIGURE 4. **BLE devices used for deploying our mesh network. (a) Waspmote device. (b) CSR1010 device.**

2) LoRa AND LoRaWAN

LoRaWAN is an open M2M and IoT-oriented standard provided by LoRa Alliance [8] classified as Low-Power Wide-Area Network (LPWAN) whose specification is intended for creating a global Wide Area Network (WAN) using devices operating under negligible energy consumption (expectations of 10-year battery lifetime). It is a stack referred to the data link layer (MAC) which uses the Long Range (LoRa [57]) physical layer (PHY) and operates in the Industrial, Scientific and Medical (ISM) radio bands. The frequencies adopted in Europe are defined in the range 863-870 MHz, which is regulated by the European Telecommunications Standards Institute (ETSI [58]) to limit some aspects of communications that are highlighted in this work.

The most extended topology for LoRaWAN networks is star-of-stars, where a central device (known as gateway) forwards packets from end-devices towards a global central network server using the Internet Protocol (IP) over Cellular or Ethernet, for instance. These networks are supposed to support thousands of devices per gateway, reaching coverage ranges up to 2 km for urban areas and 15 km for suburban areas. Although both uplink and downlink communication flows are accepted (from end-devices to the network server and vice versa), uplink networks are encouraged due to ETSI restrictions. Data Rate (DR) depends on the established bandwidth and Spreading Factor (SF), being responsible for power consumption as well as coverage area per node. For instance, a node operating under the maximum DR (corresponding to the lowest SF) mode will save the greatest amount of energy due to a short transmission consumption peak at the expense of less communication range. However, in any case the energy consumed expected from a LoRaWAN network is minimal, reason why this research stands for the use of this standard as a complementary technology for BLE networks.

The Things Network (TTN [59]) is a back-end whose mission is to build a decentralized open and crowd sourced IoT data network owned and operated by users themselves. TTN provides end-to-end encryption for deploying applications based on LoRaWAN end-devices and is based on the scheme shown in Figure 5. According to TTN back-end, registered gateways provide coverage to thousands of end-nodes, which is one of the key challenges that encourages us to deploy a LoRaWAN gateway in the Albacete Research Institute of Informatics to provide GreenIS Factory with a background network server to manage environmental data.

Since LoRaWAN has several restrictions due to the frequency bands adopted for communication, it must be highlighted that ETSI permits a maximum output power of +14 dBm (excluding the 3G band) for unlicensed bands. Furthermore, 1% duty cycle limitation is established according to the legislation applied for non-specific use bands at the frequency range of 863-870 MHz, which means that the maximum percentage of time an end-device can occupy a specific channel is 1% of its duty cycle. This fact is reflected on the operating principle of LoRaWAN-based devices and TTN Fair Access Policy to avoid collisions due to end-devices transmitting at the same time, frequency and SF. As a function of the number of nodes connected to each gateway and their SF, the number of messages per node is limited. TTN aims to provide support to, at least, 1000 nodes per gateway. In other words, it is equivalent to a limitation of 30 seconds of

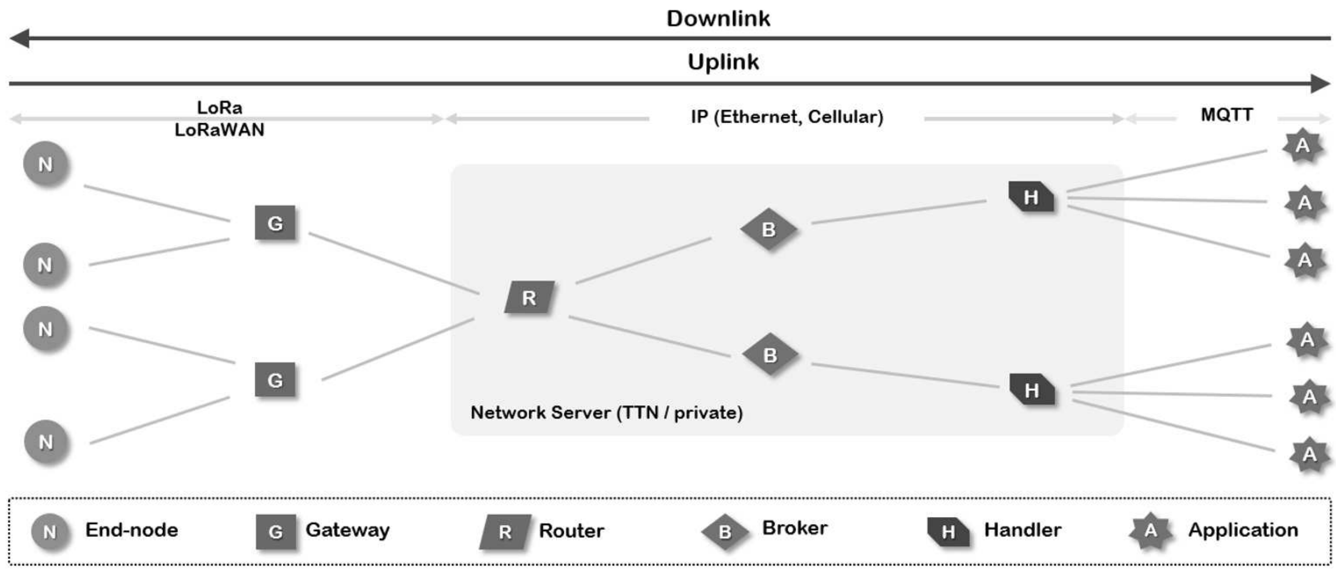


FIGURE 5. Architecture for LoRaWAN networks (from end-devices to server applications).

time-on-air per device and day, which means 20 messages per day using SF12 and 500 messages per day at SF7 at the expense of lower communication ranges.

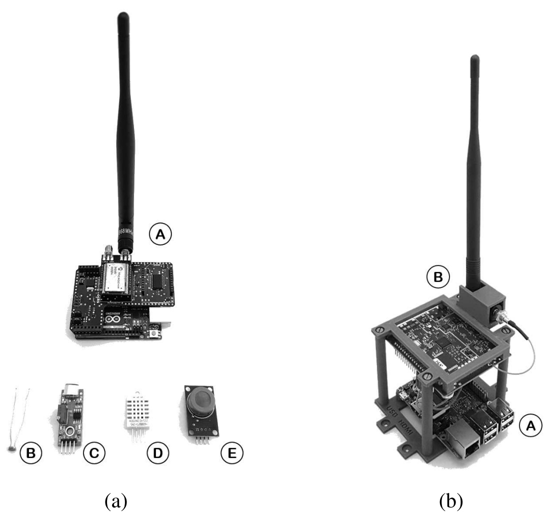


FIGURE 6. LoRaWAN devices used for the Context Network. (a) LoRaWAN end-device and sensors A: Arduino UNO and RN2483, B: LDR, C: KY-038, D: DHT-22, E: MQ-7. (b) LoRaWAN gateway A: Raspberry Pi 2B, B: iC880A.

For the deployment of our context network prototype in GreenIS Factory, one end-node has been tested using the Arduino UNO board with a shield in order to plug a Microchip RN2483 LoRaWAN radio module (see Figure 6a). Additionally, the sensors used for measuring data in the environmental network are shown in Figure 6a (from left to right: LDR, KY-038, DHT-22, MQ-7). Since LoRa and LoRaWAN are not compatible for the same applications, the selection of this module lies on the scalability of the network. LoRa is thought for P2P communication whilst, as a result of using LoRaWAN modules, we ensure that our end-devices will have the ability to send packets to a gateway already connected to the Internet. Our gateway is based on a raspberry Pi 2B board and the iC880A concentrator, whose connection is shown in Figure 6b.

B. GreenIS FACTORY

In this section we describe the scenario where the experiments presented in this work have been carried out for testing human-machine collaboration. GreenIS Factory consists of a building with an approximate area of 710 squared meters, the Albacete Research Institute of Informatics, where an heterogeneous network proposal has been deployed emulating a Smart Factory scenario. This building consists of different sectors which have been classified as separate shop floor areas within a whole factory. For carrying out the experiments, our prototype consists of a representative sector with all existing varieties of nodes coexisting and cooperating with humans. This sector is highlighted in Figure 7, where a plan view of the whole building is provided according to the deployment carried out for BLE and LoRaWAN technologies.

Since GreenIS Factory is a building where different research groups with different wireless technologies (such as Wi-Fi, ZigBee or Sigfox) coexist at the moment, it is an appropriate area to determine the degree of suitability of the network for improving social sustainability in smart factories. Furthermore, the sector where our prototype is deployed for testing the latency and reliability of the network contains furniture and machines which helps us to hinder the performance of the system and, consequently, to make it more robust for adverse environmental conditions in real shop floor scenarios. Figure 7 shows the architecture deployed in GreenIS Factory.

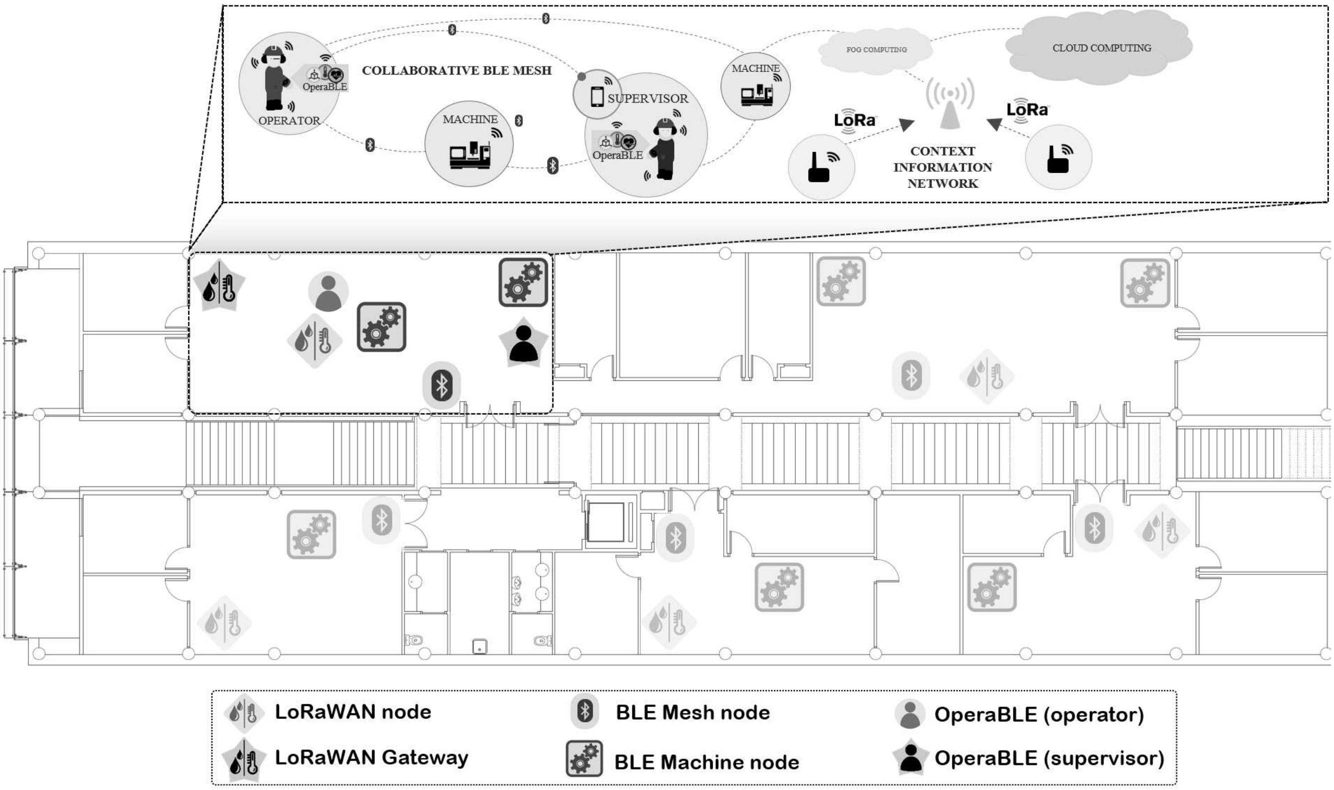


FIGURE 7. GreenIS Factory Network Architecture for human-machine collaboration.

C. BODY AREA NETWORK

The new Industry 4.0 paradigm needs to be focused on the most important entity, the human. The core of our BAN is OperaBLE, an intelligent wristband that has been developed to afford some of the main challenges of the current industrial paradigm. Two roles have been created within the industry organization: supervisors and operators. However, this challenge must be divided into two different methodologies to afford it, the improvement of security at work and the achievement of social-integration goals. The BAN introduced in this paper affords these objectives from a sustainable perspective.

OperaBLE is our intelligent wristband, responsible for monitoring movements performed by operators in order to obtain crucial information to prevent labor accidents. In cases where it is not possible to eradicate risks, OperaBLE is able to provide workers with personal assistance as fast as possible. Moreover, it helps them with the help of our fog computing techniques to improve their job according to the characterized movements.

Additionally, in this section we introduce the movement characterisation algorithm used for carrying out the experiments. Since OperaBLE has been designed to perform a double functionality, it must be highlighted that two distinct algorithms are defined in this section. The first one is related to supervisors and the second one is connected with operators.

1) SMART SECURITY TOWARDS A ZERO-ACCIDENT WORKPLACE

This paper conceives security at work as a challenge to be solved using technologies, particularly, OperaBLE and sensors embedded in industrial regulatory clothes are responsible for guaranteeing safer workplaces. The most remarkable attribute of OperaBLE in terms of security is a pulse sensor installed to measure heart rate of operators and identify risk scenarios.

Algorithm 1 shows the algorithm developed for determining heart rate and reacting to perceptible changes. According to [60], a person can be considered to be suffering stress or even fatigue when beats per minute (bpm) are increased in more than a 16% of the reference average value. As it could be an indicator of poor security conditions at work, once detected, OperaBLE manages to alert supervisors in order to evaluate individually each situation.

Our algorithm calibrates the pulse sensor during a quiet and seated state for the operator during, approximately, 30 seconds to reach the average bpm value for each individual. This calibration is only be performed once per operator and wristband, being the most important information stored in the EEPROM of OperaBLE memory. Our algorithm is based on identifying voltage peaks in the output signal of the sensor, being aware of the average and peak-to-peak reference values for each person (acquired during the calibration routine) to avoid failed measurements. The measurement routine takes

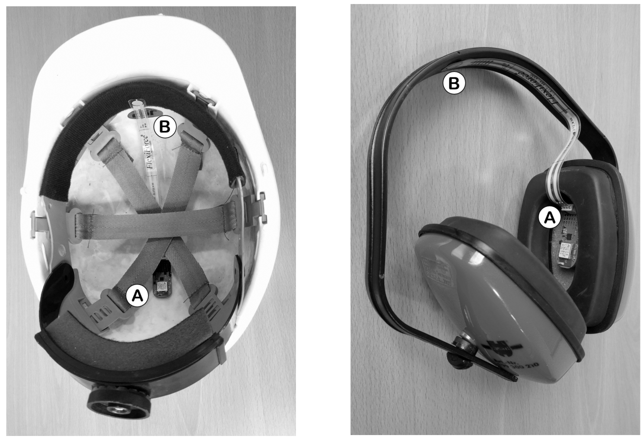
Algorithm 1 Heart Rate Measurement

procedure MAIN ROUTINE
MEASUREMENT($sampling_{frequency}$)
  if $bpm > bpm_{critical}$ **then**
    activate *warning protocol*
    increment $sampling_{frequency}$
    while *warning protocol* **do**
      if $t_{warning} > t_{threshold}$ **then**
        activate *emergency protocol*
procedure CALIBRATION($t_{duration}$)
  $V_{avg,ref} \leftarrow$ average
  $V_{amp,ref} \leftarrow$ peak-to-peak
  bpm_{ref}
procedure MEASUREMENT($sampling_{frequency}$)
  if *peak* **then**
    check V_{avg} & V_{amp} with $V_{avg,ref}$ & $V_{amp,ref}$
    $peak_{counter} \leftarrow peak_{counter} + 1$
  $bpm \leftarrow 60 * peak_{counter}/t_{measurement}$
  return bpm

place during 50 seconds and updates the calculated bpm verifying the absence of abnormal parameters.

A warning protocol has been defined in order to increase sampling periods and provide an intensive monitoring in case abnormal data is acquired. Once the warning protocol provides steady state data, if heart rate continues showing abnormal measurements (signal of fatigue or poor health), the emergency protocol will be activated in order to notify supervisors about the incidence.

Apart from measuring heart rate to ensure health and well-being at work, we have improved traditional industrial regulatory clothes such as security helmets, sound-insulated headsets and safety boots to include them into the BLE mesh network deployed. Our network provides the system with valuable information to know the relative location of operators in different shop floor areas and, thus, verify the right equipment each one should wear according to manufacturing processes. Particularly, security helmets and headsets are equipped with a LightBlue Bean board connected with a pressure sensor (see Figure 8), whilst boots include different pressure sensors to provide assistance in case of accident. Furthermore, the device embedded in the helmet, thanks to the use of an accelerometer, is able to detect impacts and send immediately an alert message to nearby supervisors.



(a) (b)

FIGURE 8. Smart regulatory industrial equipment A: LightBlue Bean, B: pressure sensor. (a) Smart protection helmet. (b) Smart protection headsets.

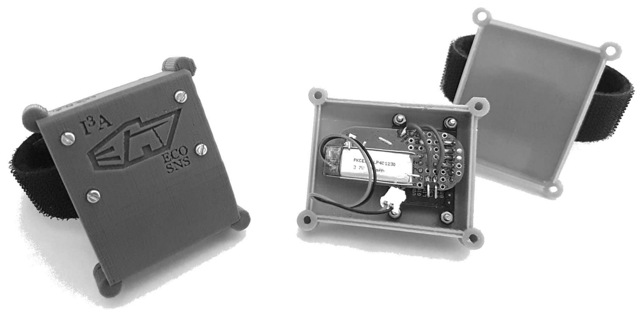


FIGURE 9. OperaBLE.

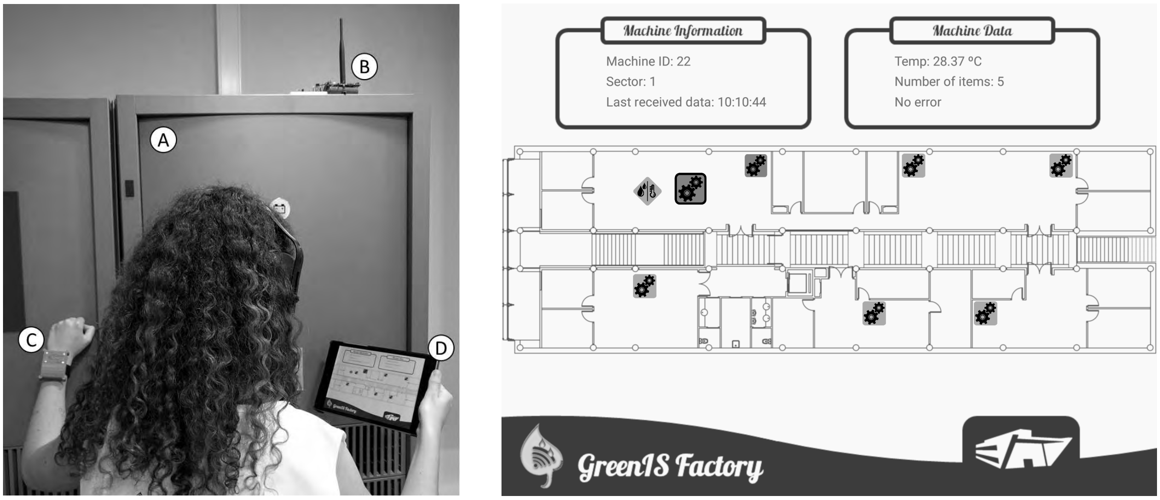
2) OperaBLE: INTRODUCING THE OPERATOR IN THE LOOP

One of the most important challenges for the next future is the integration of people who have been working with traditional techniques and, perhaps, do not have sufficient expertise in the use of new technologies. However, they have something than can provide an immeasurable added value to the final product: their experience. For this reason, we have designed our system to avoid the necessity of operators to have technological skills. OperaBLE does not have buttons and does not require previous knowledge in terms of digitalization. The key of our device to overcome this barrier is to substitute the use of screens and buttons by gesture-based interfaces, which is something intuitive that people of all ages and social conditions will understand.

The use of the movement characterisation algorithm introduced in this work improves the learning curve of operators facilitating a quick increase in individual productivity. It balances the knowledge between operators who have been recently employed and those whose experience can provide an added value. OperaBLE is able to distinguish if an action is being done correctly or not, avoiding injuries caused by a wrong use of tools and machinery. Furthermore, it provides operators with the ability of making a simple movement to notify supervisors in case of emergency. The first prototype of OperaBLE has been designed using 3D-printing techniques, which has been modeled with the shape shown in Figure 9.

3) SUPERVISOR ALGORITHM IN OperaBLE

The supervisor role has its own algorithm to recognize the motion in order to request information from machines nodes. The aim of this movement is to facilitate communication between humans and machines, reason why a double-tap



(a) (b)

FIGURE 10. Supervisor equipped with OperaBLE requesting a machine report, which is showed on the tablet application. (a) Supervisor requesting machinery reports A: machine, B: machine node, C: OperaBLE, D: mobile Application. (b) Application created for supervisor, with a machine node selected.

Algorithm 2 Supervisor Algorithm

```
procedure INTERRUPTION ROUTINE
    if tap event then
        Time register between taps
        if Enough time from previous tap then
            first tap
        else
            number of taps ++
        if Movement ended & number of taps = 2 then
            advertisement packet assembly
            advertisement packet sending
        if Movement ended then
            sleep
```

gesture action is defined to trigger some actions. The double-tap movement has been implemented using the accelerometer embedded in LightBlue Bean board. Figure 10a shows a scenario where a supervisor requests machinery reports by double-tapping the surface of the desired machine.

The device will remain sleeping until a tap is detected, moment in which it will wake up and check whether another tap is made. If a double tap is detected, a packet with the corresponding format will be prepared and sent though advertisement packet to the BLE Mesh. Thanks to the RSSI signal of OperaBLE, the machine node can detect the nearest supervisor and, therefore, if the request is intended to itself. A summarized overview of the supervisor algorithm implemented in OperaBLE is shown in Algorithm 2. Section IV-B1 provides a test carried out to check the proper operation of this system.

Moreover, an application for mobile devices has been developed for supervisors. This application uses BLE technology to take part in the BLE mesh network and permits supervisors to keep informed about all activities in the entire area of the factory. In this application, machine nodes are showed over the building plane, and double tap one of them is enough to display its information. This information is updated directly with the data packets from machine nodes transmitted by mesh network. Figure 10b shows a screenshot of the developed application, with a machine node selected.

4) OperaBLE MOVEMENT CHARACTERISATION ALGORITHM

The algorithm developed for characterizing movement from operators has been called SM-DTWN. A flexible system based on pattern recognition has been reached since it is able to learn any new movement without the necessity of stopping the entire system. The characterisation system has two main parts, three if data broadcasting through the mesh is included. It preprocesses movements to determine the beginning and the end of any movement, processing it eventually in the fog server to compare it with several patterns using SM-DTWN algorithm.

The preprocessing code developed in OperaBLE is sufficiently lightweight to avoid low data rates. It only includes the extraction of data via I2C from IMU, a first filter to know when a movement starts and ends, and the encoding of movement data to be sent through the Mesh. The processing task in our fog server, as mentioned previously, the movement characterisation is made by its comparison with movement patterns. For a better understanding of the process, a flow diagram can be seen in Figure 11. It must be highlighted that the acquisition rate in this low cost device is very poor (the usual rate is around 100Hz), reason why we have achieved a functional system operating at only 10 Hz. Thus, the recognition task turns into a much more difficult process due to the small number of samples to analyse.

Once raw movement data arrive to fog server, each axis of the received movement is decoded, and the resulting samples

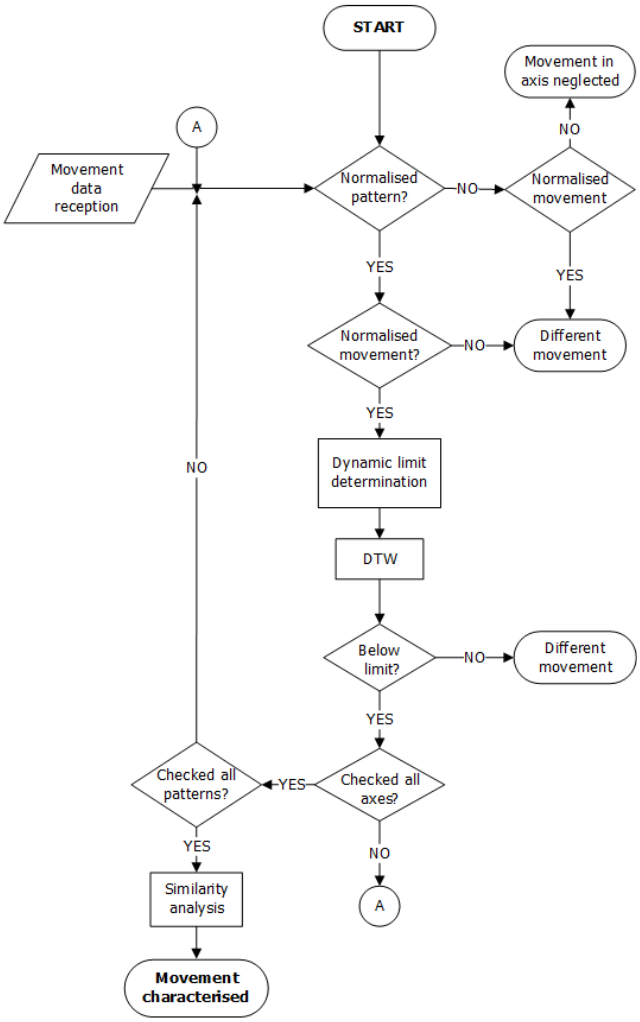


FIGURE 11. **SM-DTWN Algorithm.**

are compared with each pattern following the steps enumerated below:

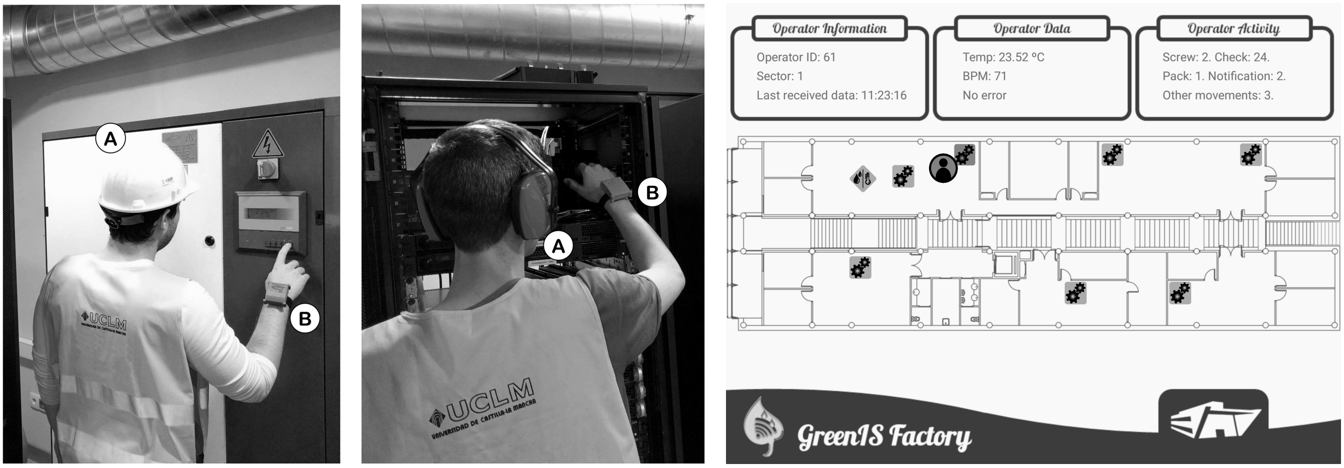
1) Relevant data is normalised to avoid the comparison between axes that have minor importance in the concerned movement. If a pattern and a movement do not have the same axes normalised, that movement is automatically devised as different from this pattern. As a result, the fluency of the fog server is enhanced.
2) A dynamic limit is assigned to the specific sample-pattern union. This provides high flexibility and permits autonomous learning for the system.
3) The Dynamic Time Warping (DTW) algorithm is applied. This iterative algorithm is able to align two time sequences to determine the similarity between them.
4) After checking all patterns, if there are several of them that could match with that movement, the closest resemblance is determined to select the most appropriate.

It is necessary to define the movements that have been characterised to evaluate the precision of SM-DTWN algorithm, which emulate routine activities in an industrial environment. These movements are: *screw*, *check* and *pack*, including an additional movement, *notification*, used by operators to call supervisors in case of incidence. The aim of this characterisation is to achieve a higher rapport between machines and operators. It provides a natural way to cooperate as well as important feedback to workers in the factory, helping supervisors to focus on operators difficulties in their daily work. Figure 12 shows two operators working with the wearables described. The movements characterised during this investigation are:

- *Screw*: rotation of the wrist from normal position, for a right-handed person, to the right and back again for three times. This is a common movement of many operators in all kind of industries, including automotive industry, assembly lines, etc.
- *Check*: movement of the hand from a neutral point (perpendicular to the vertical axis) to the piece situated about waist-high, turning the hand while ascending up to eye-level and returning again the piece to the initial position. This movement is related to industrial processes for the forming of materials where human personnel are highly used to checking the parts for quality control.
- *Pack*: action to close a box beginning with the bottom flap, then the side flaps and finally the upper flap to end the movement. The recording of this movement for OperaBLE is slightly different owing to the complexity of the action. Since there are multitude of manners to pack, for having a wide range of options for OperaBLE to compare, four patterns have been recorded. Therefore, higher flexibility to recognise the action is reached and it can be utilized in several delivery companies.
- *Notification*: Three-time repeated movement of the hand palm against any part of the body or a nearby surface. It has been designed to provide operators the possibility of sending a warning signal to the supervisor for request help in case of emergency. This tool enables rapid action thanks to the Bluetooth Mesh network deployed and the Android application developed for the supervisor.

The list of tests carried out has been performed five times to make the trial results as reliable as possible. Each sequence of four movements has been thought to avoid excessive successful results due to the repetition of movements. As a result, movements have been mixed to ensure the authenticity of test results, according to Section IV-B2.

In addition, data from operators (approximate position, bpm and surrounding temperature) collected by OperaBLE are sent periodically (or if an error arises) to fog server and supervisor application. Moreover, supervisor can request activity data from each operator selecting the operator icon. This data set permits supervisor to prevent and detect possible labor accident. Finally, if an operator makes a *notification* movement, the application highlights the particular operator to report supervisor that something is wrong. Figure 12c shows a screenshot of application displaying data from an operator.



(a) (b) (c)

FIGURE 12. Operators working in shop floor areas. (a) Operator with protection helmet A: smart helmet, B: OperaBLE. (b) Operator with headsets A: smart headsets, B: OperaBLE. (c) Application screenshot with an operator selected by supervisor.

D. BLE MESH NETWORK

As mentioned before, the current initiatives for deploying a new mesh BLE network are limited and they do not fulfill completely the requirements of the new Industry 4.0 tendency. Thus, our proposal is focused on the scalability, sustainability, total coverage and zero fails requirements. For our mesh topology, we combine two BLE standard roles:

- *Broadcaster*: this role enables broadcast data transmissions using advertisement data packets. These packets are received in all observer devices within coverage range of broadcaster. Network devices use these transmissions for sending their own data and for retransmitting data from other devices, increasing their coverage range.
- *Observer*: in this role, devices can receive advertisement data packets from other devices. If a received packet has the correct format and satisfies specific conditions, it is processed and retransmitted in broadcast again to its destination. In this way, the global coverage range is increased for each new network device.

Using the two roles described previously, we have deployed our mesh network [48]. There are some characteristics that distinguish our topology from others: firstly, we classify our mesh topology as a collaborative network because all devices in mesh network work together to retransmit every received packet. Secondly, our proposal is not a proprietary protocol, in contrast to other projects, which permits us to deploy our topology using any BLE device from version 4.0 onward. Finally, master-slave connections are not required. For this reason, any device that supports broadcaster and observer roles is able to send packets to the network and receive packets from the rest of network devices, respectively. However, it is possible to use this connection to include devices which do not implement broadcaster or observer roles. The elimination of master-slave connections has important benefits, especially in mobile devices, because they can move freely around the entire network area. Also, it avoids the need of intermediate devices, which makes scalability difficult and increases the final costs.

For the proposed mesh topology, we have defined a new packet format. This packet format is compatible with other mesh initiatives so, devices from different manufacturers can be included in our network. Furthermore, any device can communicate with any other device through the BLE mesh network, transmitting advertisement packets with this format in their broadcaster mode. The proposed format is described in [48], and it follows the BLE specification [7].

TABLE 2. Devices in our collaborative mesh network.

Device Type	Role in the network
Machine nodes	To monitor machine To warn supervisors about possible errors
Mesh nodes	To increase the coverage range of our network
OperaBLE	To check vital sings of operators To facilitate the interaction with the environment
Mobile devices	To facilitate the supervisor interaction with factory information

One of the most important aspects of the proposed topology is its heterogeneity, allowing different devices communicate among them. Table 2 shows the devices that take part in our collaborative mesh topology network.

E. LoRaWAN CONTEXT INFORMATION NETWORK

Context information is one of the most valuable features of the network since it is used to analyse the local environment of workers within smart factories. The processing context data allows our system to widen its knowledge and learn from previous experiences in order to anticipate damages in machinery or harmful working conditions for operators. Our network proposal not only manages body area information to advise workers and enhance their security at work but monitors shop floor areas to comply with existing regulations getting greener and more confortable factories.

According to national regulations which provide reference values for 1-hour exposure [61]–[63], the maximum concentration of Carbon Monoxide (CO) permitted for humans is limited to 35 ppm in indoor working areas. For the same exposure interval, the maximum level of ambient noise for a non-harmful workday is established at 87 dB(A). This reference values are essential for the context information network to ensure security at work, reason why an alarm will be triggered to alert factory workers when any of this values are exceeded. Regarding pure environmental data, temperature is supposed to remain in the range [14, 25] °C whilst humidity in the range [30, 70] %. Eventually, visual conditions must permit operators to work in environments with, at least, 100 effective lux units to avoid losses of sight or irreversible damages.

1) PROVIDING GREENIS FACTORY WITH LoRaWAN COVERAGE

GreenIS Factory is located in Albacete (Spain), where there is no coverage for LoRaWAN networks at the moment. This research provides a solution to overcome that limitation by introducing the first LoRaWAN gateway in this area, composed of a Raspberry Pi 2B board and an iC880A concentrator operating at 868 MHz (Europe frequency plan).

The multichannel gateway is intended to forward environmental data from GreenIS Factory to TTN back-end. Nevertheless, data is encrypted during the transmission process and sent to the local fog server of the factory. Since private data from workers acquired via BLE remain confidential not being accessible through the Internet, entrepreneurs can decide whether context data such as temperature, humidity or light level should be published in the cloud or stored as private enterprise information.

FIGURE 13. GreenIS Factory gateway location, source [59].

Our gateway, which is located in the sector of GreenIS Factory highlighted in Figure 13, coexists with the deployments of BLE mesh and BAN introduced by factory workers. A TTN user has been configured according to GitHub repository [64] and the Europe router for TTN back-end (eu-router) has been set for IP connections. Eventually, our gateway has been included in the repository [65] in GitHub for remote configuration based on its EUI (unique 64-bit identifier), which allows the concentrator to start forwarding LoRaWAN packets automatically once plugged in. This gateway is currently registered in TTN receiving packets from the Context Network deployed in the factory. Figure 13 shows the TTN official map [59] and the location of the gateway in the region of Castilla-La Mancha (Spain).

2) DEPLOYING THE CONTEXT INFORMATION NETWORK

Once deployed the gateway that provides coverage for the LoRaWAN network, an end-device has been configured to sense context data and send it to TTN though the gateway. Since environmental data are not expected to change in short periods of time, the sensors shown in Figure 6a have been attached to our LoRaWAN-based end-device and programmed to acquire context data. The major challenge the Context Network must face is the monitoring of working conditions for workers located in specific shop floor plants where gas leakages or harmful conditions could arise.

According to LoRaWAN specification, there are two procedures for activating an end-device: Over-the-Air Activation (OTAA) and Activation by Personalization (ABP). For carrying out the experiments, the end-device has been activated through OTAA, which facilitates roaming between different networks not permitting the owners to decrypt data unless the end-device belongs to them. TTN golden rule states a limitation of 30 seconds air-time per end-device and day, in order to permit 1000 devices per gateway in a LoRaWAN network. According to previous explanations, the air-time is dependent on DR and SF, reason why we conducted a preliminary coverage study to minimize the air-time consumed ensuring sufficient communication range for the entire building. In order satisfy coverage and TTN requirements, the experiments described in Section IV were performed under SF7, which permits LoRaWAN 10-bytes packets to be sent every 3 minutes. Section III-F provides a description of the methodology followed for gathering BLE-Mesh and LoRaWAN data in a local fog server and, thus, in the could.

Finally, context information network devices are also represented in supervisor application. This provides supervisor useful environmental information, which can help to understand what is happening in a specific area. This data is sent to application on demand using BLE from local fog server. Figure 14 shows the supervisor application displaying data from a context information node.

F. FOG AND CLOUD COMPUTING

Fog computing is a distributed computing paradigm that fundamentally extends the services provided by the cloud to the edge of the network. Advantages associated with fog computing including reduction of network traffic, suitable for IoT tasks and queries, low-latency requirement and scalability [66]. Fog and cloud Servers have been deployed in GreenIS Factory, as explained in previous sections. The reason of this division can be explained from two different points of view. On the one hand, fog server allows us to reduce cloud server traffic and to speed up the transference of data which needs to be preprocessed to become useful information. The fog server provides also data privacy for sensitive company information. On the other hand, the cloud server provides

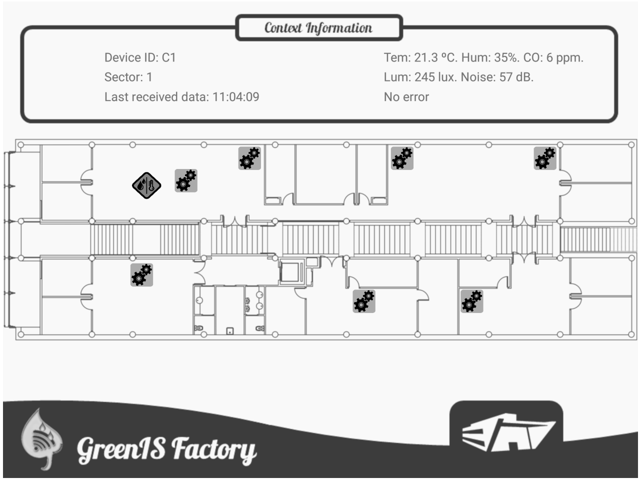


FIGURE 14. Application screenshot with a context information node selected by supervisor.

data access from everywhere, across the Internet, reducing the computing power required for future complex decision-making algorithm implementations.

The fog server implementation is divided in a modular way. Each module is independent from the others, but all of them work together to provide a full functionality. These modules are:

- BLE gateway: communicates the fog server with the BLE mesh network. This module receives data from BLE devices using our mesh topology, and pre-process it to react according to the received data. Also, this module sends information and warning messages using our BLE mesh.
- Movement characterisation: evaluates received data from BLE gateway module, comparing it with established patterns using the previously mentioned algorithm.
- LoRaWAN communication: receives context information from LoRaWAN devices, sending it to the cloud communication module. In addition, this module communicates with BLE gateway module for sending warnings and response messages.
- Cloud communication: is responsible for the communication with cloud Server, it manages both uplink and downlink packets to permit data storage and communication flow.

Eventually, the use of a global cloud sever infrastructure, such as ThingSpeak, provides a data persistence service for the network than can be accessible from any place. Two different channels have been defined: the first one, GreenIS Factory (Context Information), provides environmental data for shop floor areas where workers are performing their tasks. The second, GreenIS Factory (Labor Activity), includes private information on operators heart rate, production and movements statistics. Entrepreneurs are responsible for deciding whether these channels are publicly available or not, which provides an added value to factory information and security at work.

IV. RESULTS AND DISCUSSION

This section provides a brief description of the configuration and conditions established for carrying out the experiments, as well as the analysis of their results. Several experiments determined the functionality of the entire system, considering the baseline of a BLE mesh network which satisfies the zero-fail, full coverage and real-time Industry 4.0 requirements for human-machine collaboration.

Once the core of the network was tested, some experiments were carried out in order to verify how our system introduces operators in the loop by ensuring their security at work and enhancing the labor conditions. These experiments include movement characterisation to enhance the learning curve of operators, heart rate measurements combined with regulatory clothes verification to ensure legal working conditions and, eventually, a set of context parameters monitoring in order to improve working environments according to human well-being.

A. EXPERIMENT 1: BLE MESH NETWORK

In [48], we proposed a BLE mesh network with sensor nodes and mesh devices with different configurations according to the role played by these devices in the network. In this way, for mesh configuration, individual (only mesh devices retransmit the received packets) and collaborative (all devices retransmit the received packets) modes were proposed. For each mesh configuration, two different settings were evaluated in machine and mesh nodes, changing the number of times a received packet is retransmitted.

For the experiments performed in this section, a collaborative mesh configuration has been selected, with mesh and machine nodes retransmitting each received packet only once. We selected this configuration because: firstly, our topology should be a collaborative mesh to provide total coverage in a real factory; and secondly, this is the lowest network traffic collaborative mesh configuration, which is an important point in sustainability objective.

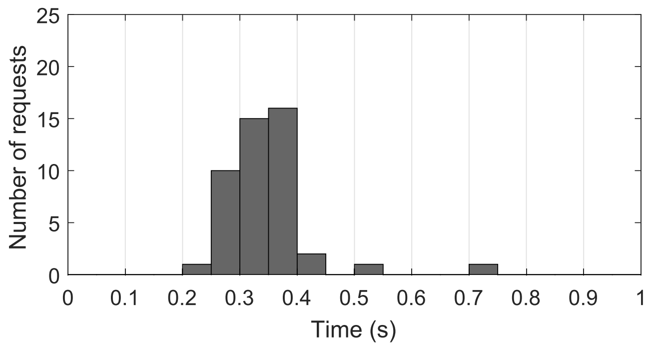
These new characteristics are proposed to facilitate the work of the users and to prevent occupational risks, among others. For this reason, the performance of the communication of these new characteristics is evaluated in this section. In this new communications, we can find the requests made by supervisor using the mobile device, after which the response from server must be received. In addition, different packets related with movements appear: taps and movement characterisation.

1) SUPERVISOR REQUEST THROUGH A MOBILE DEVICE

The first evaluated characteristic is data request. As already said, a mobile application has been developed to facilitate the task of the supervisor. Although all sensor data are updated in real time (taking advantage of the use of the BLE mesh network), certain information is sent on-demand, either because it is transmitted using another network (context information transmitted by LoRa network) or because it needs to be

Successful request	Successful response	Average time
100%	92%	0,347 s

(a)

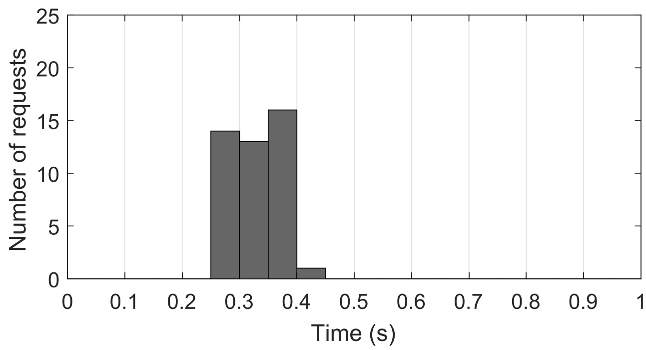


(b)

FIGURE 15. **Results obtained for operator information request from supervisor. (a) Summary of experimental results. (b) Histogram of time lap from sending request to receiving response.**

Successful request	Successful response	Average time
100%	88%	0,318 s

(a)



(b)

FIGURE 16. **Results obtained for context information request from supervisor. (a) Summary of experimental results. (b) Histogram of time lap from sending request to receiving response.**

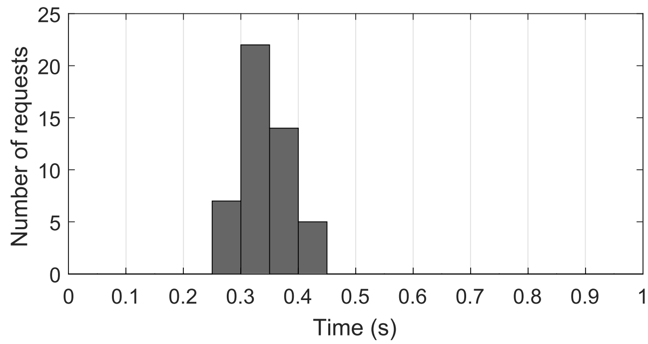
preprocessed (user movement). However, possible errors are notified without previous request.

For this evaluation, three sets of 50 request have been tested. In the first set (Figure 15), only operator data have been required. For the second set (Figure 16), only requests for context information have been made. Finally, in the third set (Figure 17) operator and context information has been demanded, alternatively. For each set, the percentage of successful requests (received by the fog server), the percentage of successful responses (received by mobile supervisor device) and the request-response time interval have been measured.

For operator data requests (see Figure 15a), all request packets have been received and processed in the fog server

Successful request	Successful response	Average time
100%	96%	0,359 s

(a)



(b)

FIGURE 17. **Results obtained for context and operator information request from supervisor. (a) Summary of experimental results. (b) Histogram of time lap from sending request to receiving response.**

(50/50 successful requests), although some response packets have not been received (48/50 successful responses). Figure 15b shows the histogram of the time elapsed between a request and its response, for each successful received response.

Results for context information requests (see Figure 16a) are similar: fog server has received and processed all request packets (50/50 successful requests) and not all response packets have been received in mobile device (47/50 successful responses). The request-response time interval is shown in Figure 16b.

Finally, for alternative requests (operator data and context information), the results are close to results obtained previously (see Figure 17a): all request packets have been received and processed by fog server (50/50 successful requests), and only one response packet was lost (49/50 successful responses). Figure 17b includes the request-response interval time.

As seen in these experiments, most packet losses are produced in response packets from BLE gateway to mobile device, in contrast with perfect request packet transmissions from mobile device to BLE gateway. This situation is probably produced due to the way in which retransmissions are managed. The BLE gateway implements a buffer to store packets which will be retransmitted when possible, spending the minimum time as broadcaster. However, mobile device retransmits a packet as soon as it is received, to avoid an important workload in mobile device. This causes that the scanning time is not as delimited in mobile device as in BLE gateway.

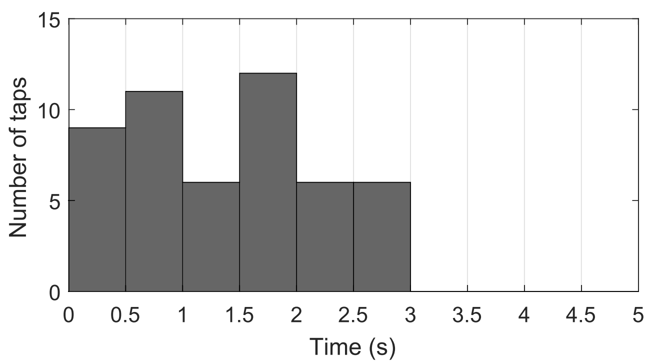
Regarding user experience, two factors appear: on the one hand, the time interval between the supervisor selects a device or operator in mobile application (which triggers a request) and the response is received; on the other, the probability of these responses are received. In our experiments, we have obtained, on average, a response time of 0.341 seconds and a probability of 92%. This provides a good user experience for supervisors in our application. In addition, this probability could be improved resending the request packet if no response is received.

2) SUPERVISOR REQUESTS USING OPERABLE TAPS

Machine nodes have been programmed to send their performance data when a time interval has elapsed. This time interval can be modified, and for our evaluation it has been set to 15 minutes, unless an error is detected or an uncommon value is measured. However, supervisor can request current information from machine nodes near him, using the *tap* movement. When this movement is detected by the OperaBLE device, and supervisor is close enough to a machine node, this wearable sends a request packet to machine node. Machine node updates its data and sends a new and updated packet to supervisor mobile device and to fog server using mesh BLE network.

Detected in machine node	Received in server	Average time
100%	96%	1,407 s

(a)



(b)

FIGURE 18. Results obtained for context and operator information request from supervisor. (a) Summary of experimental results. (b) Histogram of time lap from sending tap packet (from OperaBLE) to receiving response (in server).

For this evaluation, 50 requests have been made to two different machine nodes, alternatively, using the *tap* movement and verifying the correct data receiving in mobile device. Results are showed in Figure 18. Figure 18a contains the percentage of requests received by machine node and the percentage of data packets received by mobile device triggered by these requests. Results show how all request packets are received in sensor node (50/50 successful requests), although some data packets from sensor nodes are lost when they are sent to supervisor mobile device (48/50 successful data packet receiving). Figure 18a also shows the average time elapsed between a *tap* movement detection and a data packet from sensor node is received. In addition, Figure 18b show the time for each request-response.

As in the previous experiment, the number of responses received in mobile device is lower than the number of requests received in machine node from OperaBLE. However, in this case, machine nodes are using BLE 4.0, and its high percentage of received packets is due to the source device: OperaBLE. This device has been developed using LightBlue Bean, because of its low power consumption and its small size. However, broadcaster role has been recently included in its firmware and it is no possible to sent a single advertisement packet. For this reason, more than a packet is sent, increasing the receiving probability in machine nodes.

In addition, the time since the movement is finished until data packet is received by mobile device is a good way to evaluate the user experience. In this experiment, the time has been, on average, 1.407 seconds. However, this type of interaction is different from others, because it is done with the environment itself, in a simple and understandable way.

3) MOVEMENTS TRANSMISSION BY THE MESH NETWORK

Transmissions of movement data packets is the last evaluation of our mesh network performance. When a movement is done, the data collected by the accelerometers integrated in OperaBLE is sent to fog server for its processing and characterisation. Moreover, the size of data collected for a movement is usually larger than the packet data unit size (for this field type, the length is 12 bytes). For this reason, fragmentation of movement data in source device and reassembling it in the fog server is necessary. However, this methodology can produce movement data losses if one of its packets is lost in the transmission.

Table 3 shows the evaluation for 50 movement data transmission. These 50 movements produce a total of 481 data packets. Although the packet loss rate is only 0.42%, it implies the loss of two complete movements (4%), because full movement data is required for analyzing.

TABLE 3. Results for evaluation 50 movement data transmissions.

Total Packets		Total movements		Average time per packet
Sent	Received	Sent	Received	
481	479	50	48	0.290s

This packet fragmentation makes the size of the movement data (which is determined by the movement duration) directly proportional to the time necessary for data transmission. Figure 19 shows the time required for transmitting different data size movements, according to the number of packets used for sending them. In addition, this experiment was carried out using two OperaBLE devices simultaneously, and the results demonstrated that there is no significant variation in the time required. This happens because the bottleneck of the mesh network remains in source devices, not in the intermediate mesh devices.

For each movement, samples are collected each 100 milliseconds. Each sample has a length of 6 bytes. As said before, the size of packet data unit available for data is 12 bytes, so each packet contains up to two samples, which

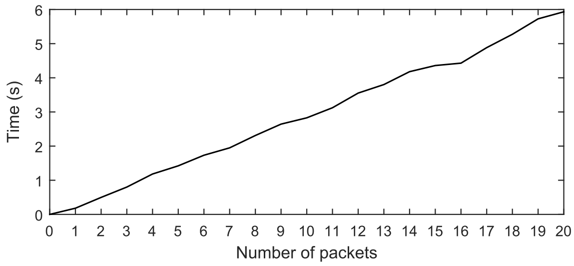


FIGURE 19. Time required for transmitting movements according to their number of packets (data size).

are transported to fog server. In this way, the transmission time depends on the movement duration. For example, for a 2-second movement, 10 packets are sent to fog server for their reassembling and processing. However, these movements are used for statistics to ensure the operators work correct and safely.

In addition, there are two options to improve this movement transmission: the first option is to send a request to OperaBLE for lost packet repetition, while the second option is to create the lost data according to the rest of the received data.

B. EXPERIMENT 2: HUMAN-MACHINE INTERACTION IN OperaBLE

These tests were carried out to obtain real values and exact information about OperaBLE and its suitability in GreenIS Factory. We focused on the accuracy of algorithms developed regarding the roles supervisor and operator.

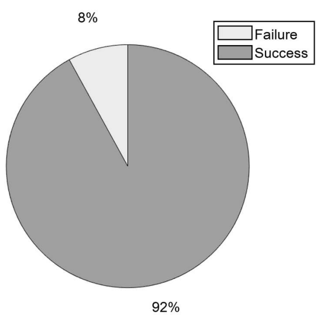


FIGURE 20. Supervisor Taps test results.

1) SUPERVISOR REQUEST MOVEMENT TEST

This test has been carried out to check success percentage of Supervisor Algorithm regarding the detection of the request action. The movement is made 50 times, Figure 20 shows the results of this experiment. Since it is not a critical movement, an error percentage around 8% is acceptable and provides a satisfactory user experience.

These results could have been even more accurate if another device with a high clock frequency was used. Since the main problem is that the device used to measure these taps has a low working frequency, there are some situations where the device takes too much time to run the program and wake up, hence, the established time limits are exceeded.

Another graphic can be seen in Figure 21. It shows when an advertisement is produced thanks to the measurement of power consumption in OperaBLE. This is interesting as well for realizing the real power consumption demanded when using interruptions. A set of taps was executed in a sequence which included the following number of taps: 1, 2, 3, 5, 2. Therefore, when the number of taps matches with the double tap action, the advertisement is produced. In the graphic above consumption is directly represented although it is difficult to distinguish each variation properly. For this reason, the graphic below illustrates the same consumption by applying a moving average filter with 20 samples span. It offers a clearer view of the events that we want highlight.

We can notice in all movements a first current peak that is the consumption related to wake up operation. In cases where two taps were not made there is no peak associated to the advertisement sending, reason why the consumption is linked only to taps and operations of the program. However, in the case of double tap action, another peak can be seen at the end of the program, this is the advertising process. Regarding power consumption, it can be observed that the mean approaches 14 mA when the program is running while the power consumption is around 2 mA when the device is in sleep mode. It the utility of using an interruption mode in this sort of applications where the battery saving is a critical aspect.

TABLE 4. Operator movements test.

	1^{st}	2^{nd}	3^{rd}	4^{th}
Sequence	Notification	Check	Pack	Screw
	Check	Pack	Screw	Notification
	Screw	Notification	Pack	Check
	Pack	Notification	Screw	Check
	Screw	Check	Pack	Notification
	Check	Notification	Screw	Pack
	Pack	Screw	Notification	Check
	Notification	Screw	Check	Pack
	Check	Pack	Notification	Screw
	Notification	Check	Screw	Pack

2) OperaBLE: CHECKING SM-DTWN ALGORITHM

This test has been thought to verify the proper operation of SM-DTWN algorithm for recognizing movements, particularly, the four movements that have been recorded in the system: *screw*, *check*, *pack* and *notification*. Ten different sequences that include the four actions have been performed (five times each one) to obtain a reliable result. All of them have been made in each sequence, however, intending to preserve the integrity of the test, they are made in an alternating manner (see Table 4).

The resulting percentages of success are shown in Figure 22. We can notice that the algorithm is very precise in short movements as *check* and *notification* achieving one

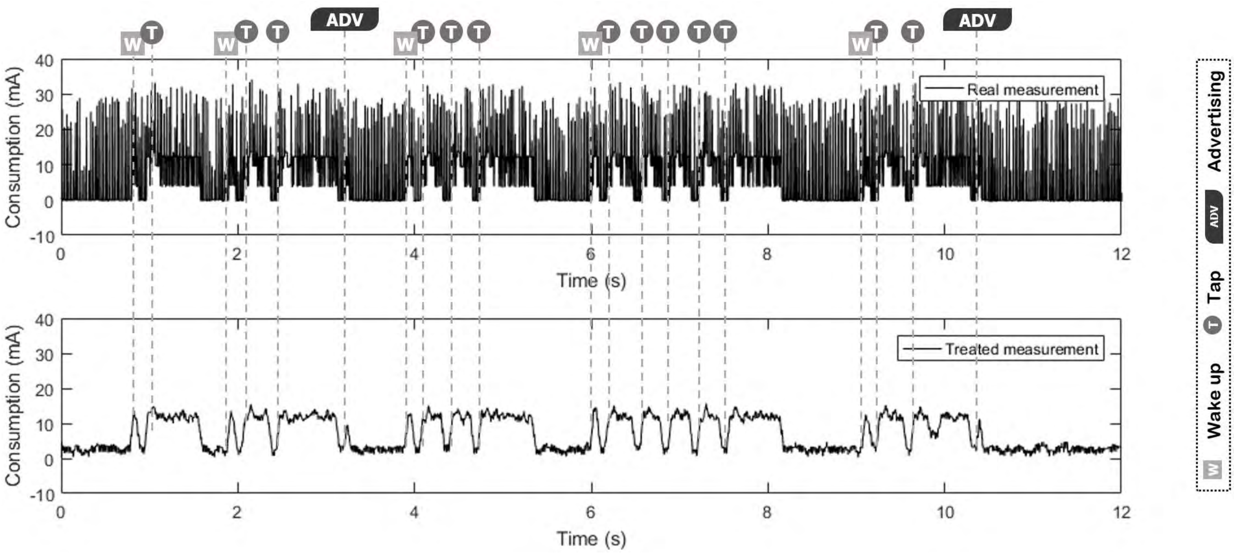


FIGURE 21. OperaBLE notification consumption.

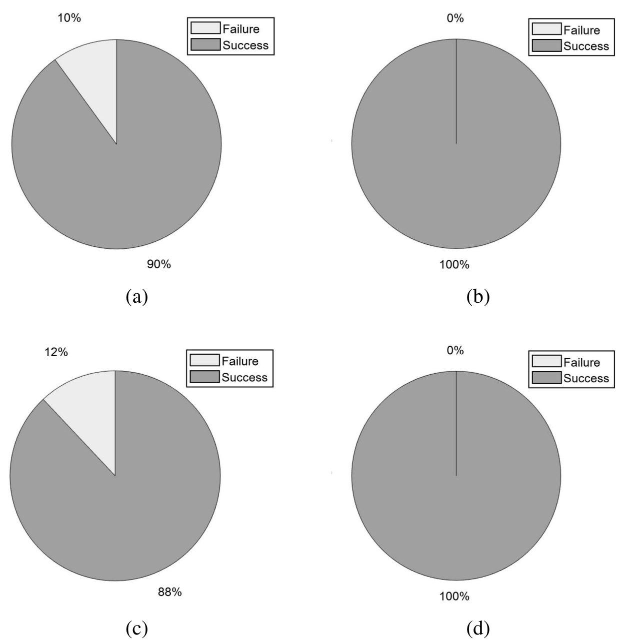


FIGURE 22. OperaBLE movements test results. (a) Screw. (b) Check. (c) Pack. (d) Notification.

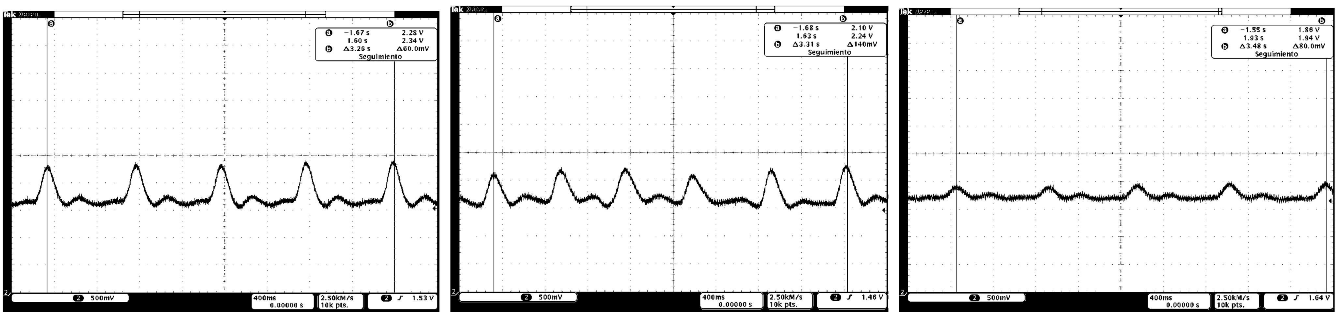
hundred per cent of success in both cases. This occurs due to the simple fact that the shortest movements can be easily repeated with a minimum error. Conversely, *Pack*, is the only movement that was recorded with more than one pattern, in particular four, because there are many ways for making this action. In fact, the reason why this pattern reaches the lowest success percentage remains in the complexity of the action. Thus, the system has been implemented enabling the recording of patterns with the same name to improve the recognition accuracy. The *Screw* movement had a lower percentage of success than the previous ones.

It must be noticed that, although there were some failures, in all cases (except one) the movement detected was *notification*. After a deeper investigation it has been concluded that they had enough similarities to produce this result because of the number of repetitions (three in both cases), the vertical movement and the high speed of execution. This mixture caused that both movements were recognized and, as mentioned previously, SM-DTWN Algorithm selects the pattern with lowerst differences according to DTW Algorithm. In those cases, *notification* had a lower difference due to the dynamic limit assigned to a short movement compared to a longe one. There are several alternatives that could solve this problem: a more accurate recording of the movement, the implementation of the SM-DTWN Algorithm in a device with a higher sampling frequency or even using a higher number of variables (such as angular velocity) to augment the axes used to compare during the process.

C. EXPERIMENT 3: REINFORCING SECURITY AT WORK

This experiment was performed in order to ensure acceptable working conditions for operators according to the right use of regulatory industrial clothes. During the experiment, BLE wearables monitored whether the operator was wearing the smart headsets and helmet described in this work (when necessary). Thus, every time the operator was not wearing the equipment when expected, an indication LED was turned on and sensors embedded in clothes notified nearby supervisors. Moreover, our heart rate measurement algorithm was tested with different individuals to verify the degree of fidelity of the data acquired by OperaBLE in working environments.

Three workers were taken as reference for the experiment, and three measurements were performed in fatigue, relax and working conditions for each one of them. Table 5 shows the measurements carried out where, compared with the ones



(a) (b) (c)

FIGURE 23. Oscilloscope pulse samples for three operators under different conditions. (a) Operator 1 (relaxed). (b) Operator 2 (fatigued). (c) Operator 3 (working).

TABLE 5. Heart Rate measurements (bpm) in different conditions.

	Amp (V)	AVG (V)	Measured (bpm)	Real (bpm)	Error (%)
Fatigued$_1$	0.21	1.72	89	90	1.11
Relaxed$_1$	0.61	1.81	74	73	1.37
Working$_1$	0.29	1.75	72	70	2.86
Fatigued$_2$	0.62	1.76	89	109	18.35
Relaxed$_2$	0.31	1.72	55	56	1.79
Working$_2$	0.53	1.82	43	44	2.72
Fatigued$_3$	0.49	1.75	83	83	0
Relaxed$_3$	0.23	1.70	68	68	0
Working$_3$	0.39	1.74	65	63	3.17

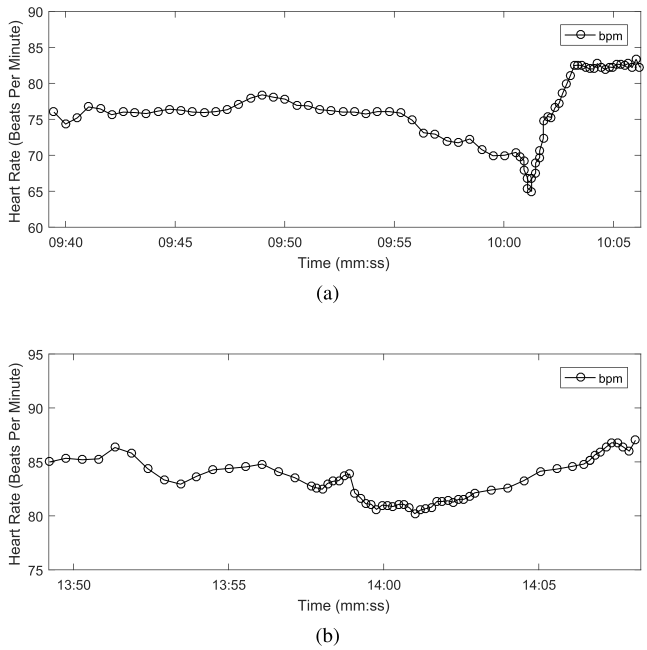


FIGURE 24. OperaBLE heart rate results for different fatigued individuals. (a) Warning and alarm protocols triggered. (b) Warning protocol triggered.

obtained by the use of a digital oscilloscope. Figure 23 shows the output of the oscilloscope for three of the measurements provided in Table 5.

Figure 23a corresponds to the first individual under relaxed conditions, whilst Figures 23b and 23c are measurements from the second and third individual under fatigue and working conditions, respectively. These measurements are the most representative for: average, (Figure 23a), maximum (Figure 23b) and zero (Figure 23c) error.

Our results show the degree of fidelity obtained by the heart rate algorithm introduced in this research, whose error rate approaches 3% considering an average value. However, a maximum error of 18.35% was obtained for the fatigued state of the second individual. Although the bpm value obtained during calibration was correct, once Operator 2 started to feel fatigued his skin began to sweat. This fact increased the difficulty for the sensor to reach a steady state pulse pattern (see Figure 23b), which provoked our algorithm to miss certain peaks. Low cost devices such as SEN-11574, the sensor used for the experiments, are susceptible to this kind of reactions in the skin of individuals, reason why our algorithm focuses on the calibration of the sensor in order to set the reference values for each operator. Thus, wrong measurements are avoided and only progressive heart rate increments are considered for warning and emergency protocols.

Heart rate calculation is additionally affected by the amplitude of the signal. Since signals with large amplitudes offer a better resolution for the peaks to be measured by the sensor, the excess of information could be disruptive for the algorithm performed by OperaBLE. In these cases, better results could have been obtained by softening the output signal of the sensor in a preprocessing stage to simplify the raw data OperaBLE must analyse, which is proposed as a future work for this research.

Apart from the previous measurements and calculations, our algorithm was tested for two individuals working under different conditions, who were stimulated to experience fatigue. For the experiment, a 5% increase in bpm was considered to be a fatigue state (instead of the 16% defined in methodology) to trigger the emergency protocol and notify supervisors. These two scenarios were monitored, whose data (received in ThingSpeak cloud [9]) is provided in Figure 24).

In view of the results for the first experiment (see Figure 24a), when abnormal conditions are detected

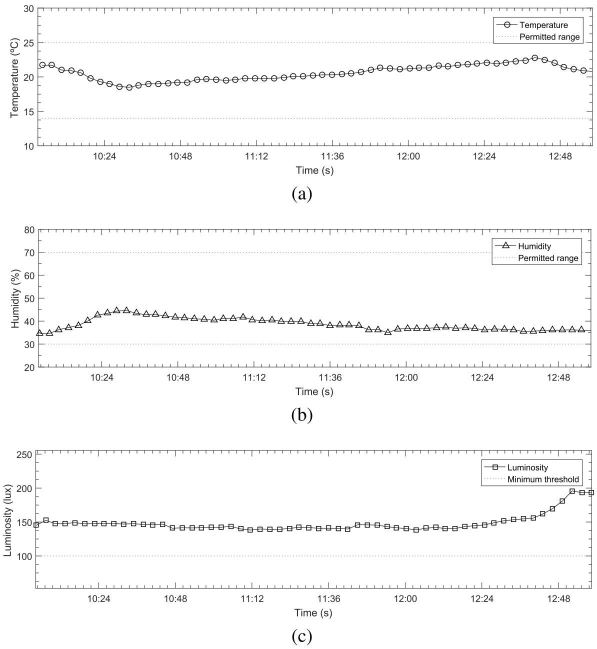


FIGURE 25. Context information received in ThingSpeak cloud (LoRaWAN network). (a) Temperature. (b) Humidity. (c) Luminosity.

by OperaBLE, the sampling frequency increases in order to provide an intensive monitoring and decide whether it is necessary or not to send supervisors a report of the conditions detected. In this case, the warning protocol was triggered by unexpectedly low bpm measurements, which suddenly increased from 65 to 84 bpm during a short period of time. This fact eventually caused the transition from the warning to the emergency protocol to notify supervisors about the strongly abnormal heart rate data acquired from the operator. Conversely, the second experiment (Figure 24b) represents an scenario where, although the warning protocol was activated by OperaBLE, it perceived a state stable enough for not to trigger the emergency protocol. Nevertheless, three minutes after stabilization, the heart rate started to increase and OperaBLE activated the warning protocol to track the operator.

D. EXPERIMENT 4: TOWARDS WORKERS WELL-BEING

The final experiment performed in the network prototype concerned the monitoring of context data measured by LoRaWAN network. Since a single LoRaWAN end-node was deployed in GreenIS Factory to verify its cooperation with the BLE Mesh network, the environmental parameters were measured individually in three-minute intervals to ensure healthy conditions at work according to national regulations. Figure 25 shows the most representative parameters measured in GreenISF by the Context Network during three hours of the working day. Particularly, Figure 25a provides temperature measurements, Figure 25b humidity and Figure 25c luminosity, where limitations for each magnitude according to national regulations have been remarked.

During the experiment, LoRa-based information was sent to TTN (being retransmitted by the gateway deployed in GreenISF). This information was sent from TTN to a local Fog server, where entrepreneurs could decide whether data was posted periodically in public or private ThingSpeak channels. At the moment, the cloud channels created for the experiments are being used to collect data under the names ‘‘GreenISF (Context Information)’’ and GreenISF (labor Activity).

V. CONCLUSIONS

This work investigates key enabling IoT technologies towards collaborative networks in Industry 4.0 environments. Particularly, the deployment of an heterogeneous network based on BLE and LoRaWAN technologies is afforded in order to encourage sustainable techniques and algorithms to avoid social disruption caused by the incoming industrial paradigm.

GreenISF is introduced in this research as a Smart Factory scenario where the network prototype has been deployed. For this, different roles have been defined for testing human-machine collaboration, including operators, supervisors, machines, smart devices and static nodes. Nevertheless, the core of the network deployed is OperaBLE, our smart wristband prototype designed to promote human-centered architectures in Industry 4.0 scenarios.

The novel case studio analyzed in this work encourages human-in-the-loop integration by means of BANs driven by wearables (WearBANs) in Smart Factories. This work introduces SM-DTWN, an algorithm able to characterize operator movements leaving aside knowledge differences and technological skills. Operators have been provided with a smart assistance system implemented in OperaBLE as well. Regulatory industrial clothes have been improved for augmenting security at work, complemented with a pulse measurement algorithm which is introduced in this work for heart rate monitoring. Moreover, a mobile application has been developed to provide up-to-the-minute information from machines, operators and context to supervisors. In this way, the interaction with the factory environment is faster and easier, allowing immediate response to unexpected events.

A real collaborative BLE mesh network has been deployed and evaluated to fulfill Industry 4.0 requirements: zero fails, total coverage and sustainability. Experiments have demonstrated how this proposal improves the current standard BLE topologies and other mesh initiatives for this use case.

The deployment of a LoRaWAN Context Information Network promotes safer workplaces and prevents operators from harmful environments. The case study focused on this research has been tested in GreenISF in order to acquire context data and cooperate with the BLE Mesh network, where personnel are immersed by means of OperaBLE. As a result, we have achieved a major challenge for Industry 4.0: human-machine fusion towards social and sustainable factories.

The entire network is connected to a local fog server where raw data is preprocessed to extract the relevant information that will be stored in a cloud infrastructure. This hierarchy permits the private local storage of sensitive data acquired from personnel and machinery. The development of a cognitive system is proposed as one of the principal future works for this research in order to enhance intelligent support systems in smart factories. Furthermore, machine learning techniques could be applied to complement our movement characterisation algorithm and achieve an autonomous learning system. The BLE mesh network proposed in this case study will be improved so as to optimize communication towards sustainable and secure industrial environments.

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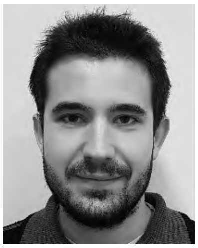
CELIA GARRIDO-HIDALGO received the B.Sc. degree in industrial electronics and automation engineering from the University of Castilla-La Mancha, Spain, in 2015. She is currently pursuing the M.Sc. degree in industrial engineering and researcher with the Albacete Research Institute of Informatics, Advanced Communications and Computer Architectures. Her principal research fields are wireless sensor networks, Internet of Things, and industrial Internet, focusing her investigation on BLE architectures for smart buildings and low power wide area networks such as LoRaWAN and Sigfox.



DIEGO HORTELANO received the B.Sc. and the M.Sc. degrees in computer science and engineering from the University of Castilla-La Mancha, Spain, in 2013 and 2015, respectively, where he is currently pursuing the Ph.D. degree in advanced computing technologies. In 2015, he joined the Laboratory of High-Performance Networks and Architectures, Albacete Research Institute of Informatics, as a Research Assistant. His main research fields are Internet of Things, wireless sensor networks, and wireless communication protocols, especially focused on Bluetooth low energy technology.

LUIS RODA-SANCHEZ received the B.Sc. degree in industrial electronics and automation engineering from the University of Castilla-La Mancha, Spain, in 2016. He is currently pursuing the M.Sc. degree in industrial engineering with the Albacete Research Institute of Informatics, Advanced Communications and Computer Architectures. He is also a Researcher with the Albacete Research Institute of Informatics, Advanced Communications and Computer Architectures. His principal research fields are Internet of Things, wireless sensor networks, human–machine interaction and wearables development, particularly focused on accelerometer-based movement characterization algorithms.

TERESA OLIVARES received the Ph.D. degree in computer science from the University of Castilla-La Mancha in 2003. She is currently an Assistant Professor with the Department of Computing Systems. She is a member of the research group High-Performance Networks and Architectures, Albacete Research Institute of Informatics. Her main scientific research interest includes Internet of Things standards, protocols and communications, low power wireless sensor networks, smart environments, body area networks, and proximity networks. She has supervised two Ph.D. students, and currently, he advises other Ph.D. students. She has very interesting publication in these areas and she participates on interesting sensor-based research projects.

M. CARMEN RUIZ received the M.Sc. degree in computer science from the University of Murcia, Spain, in 1997, and the Ph.D. degree in computer science from the University of Castilla-La Mancha in 2007. From 1990 to 1999, she works in Madrid, Spain, and London, England, in several private enterprises as an Analyst/Programmer and as a Project Manager. She is currently an Associate Professor with the Department of Computer Systems, University of Castilla-La Mancha. She is a member of the research group Real-Time and Concurrent Systems, Albacete Research Institute of Informatics. She has published research papers in reputed international journals of mathematical and engineering sciences. Her current research interests include network planning, wireless communications, traffic modeling, and wireless network evaluation by means of formal methods and performance evaluation.

VICENTE LOPEZ received the B.Sc. degree and M.Sc. degree in computer engineering from the University of Castilla-La Mancha, Spain, in 2001 and 2014, respectively. He is currently pursuing the Ph.D. degree. His primary research areas are computer networks and human–computer interaction, based on IoT technologies.