Reconfigurable IoT Solution for Train Integrity and Monitoring

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***Abstract*—This article proposes an IoT system that ensures the integrity and monitoring of railway circulating material, where the network is self reconfigurable and its devices are not physically connected or used with redundancy. The system is based on a wireless sensor network (WSN) that facilitates communication among devices and transmits data from train sensors to a gateway while considering power consumption. Bluetooth low energy (BLE) mesh features enable the relay of data between devices and the network reconfiguration. If network reconnection is not possible, the device can use LoRa communication to report its position directly to the control center. Different disposition conditions were applied to the WSN, and the results indicate that this system is viable in terms of network configuration and self regeneration. Furthermore, it has a current consumption of less than 1 mA during its low power mode,with the integrity of a 50 node model train can be reported in an average time of 2.63 s.**

***Index Terms*—Bluetooth low energy (BLE) mesh, Internet of Things (IoT), LoRa, low power, reconfigurable, reliability, train integrity, wireless sensor network (WSN).**

I. INTRODUCTION

INTERNET of Things (IoT) refers to the network established between physical devices, software, sensors, software and items with electronics that enables the objects to connect and commute data with other systems. The devices can range from common domestic gadgets to complex industrial gear, being able to collect and share information without human input.

The IoT technology is being explored for different fields and applications, as it offers promising solutions that can result on the performance improvement of systems [1]. IoT has been deployed for industrial projects in areas such as logistics, agriculture, car industry, surveillance, environmental monitoring, and others, where it could be set up in challenging places and conditions [2], [3], [4], [5], [6], [7]. With this technology it can be avoided dangerous and costly human procedures; however, harsh environments may also prevent a device from properly functioning or even deteriorate it, reducing the gadget's lifetime. This includes exposure to high levels of vibration, temperature fluctuations, and severe weather conditions.

Despite its vast potential, the implementation of IoT solutions in demanding settings presents formidable challenges [8]. Power consumption is a crucial factor, as new features often come with increased energy usage. To overcome this, energy-efficient technology and compact design must be used, aiming for smaller and more compact devices. Additionally, the cost of manufacturing must be considered when selecting electronic components for embedded systems, as the goal is to optimize cost while still meeting the desired function of the device. This is particularly true in industries with harsh operational conditions, such as the railway sector. The railway industry, with its unique demands for connectivity and data sharing, stands to benefit significantly from innovative IoT applications. However, the intricacies of onboard train integrity and monitoring require robust solutions that can withstand environmental adversities and ensure uninterrupted functionality.

Deploying IoT network devices poses several challenges, including connectivity, platform compatibility, and data management. Connectivity involves establishing a stable and reliable connection between devices, applications, and cloud services, which is difficult in harsh environments and requires careful planning. Another challenge is ensuring that new IoT devices and advancements work seamlessly with legacy systems and networks. Lastly, effective data management is crucial for securely collecting, storing, and processing data in the appropriate location. Ensuring that data is handled properly is essential for the success of any IoT deployment.

Within the different applications and technologies in IoT, wireless sensor networks (WSNs) can be used as a monitoring technique for an IoT system. Advancements in computer networks and M2M communications have led to the development of small-scale networked sensors, creating a new field with endless possibilities for real-time applications. This technology provides a digital connection to real-world objects through WSN [9].

This study investigates the application of a bluetooth low energy (BLE) mesh network in conjunction with LoRa communication to address the connectivity and data sharing challenges within demanding environments, specifically focusing on the railway industry, particularly onboard train integrity and monitoring. The proposed system establishes a resilient communication infrastructure by interconnecting

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WSN nodes through a BLE mesh network. This mesh network not only facilitates the seamless exchange of data among nodes but also ensures a robust connection even in harsh railway conditions. Notably, the network exhibits a remarkable capability for self-healing and self-reconfiguration, allowing for the removal or reordering of nodes to optimize network performance. Moreover, the utilization of low-power modes and configurations for individual network devices contributes to a reduced demand on power supply. In cases of node failures, the system employs long-range communication to relay the position, enhancing the overall reliability and integrity of the train monitoring system.

In essence, this study underscores the pivotal role of BLE mesh technology in maintaining connectivity and functionality in challenging operational environments within the railway industry. By addressing the unique challenges posed by onboard train integrity and monitoring, our proposed solution contributes to the advancement of IoT applications in critical industrial settings.

This article is organized as follows: Section II addresses the state of the art for railway environment applications. The communication system approach is presented in Section III; system architecture is described in Section IV, including the device setup and its workflow. Results are displayed in Section V, and conclusions are presented in Section VI.

II. RAILWAY ENVIRONMENT: STATE OF THE ART

In the railway environment, there are different IoT systems explored for different applications, either onboard or along the track [10].

The integration of condition monitoring systems onto train wagons requires consideration of three key factors: power, mechanical durability, and communication technologies to use. As electric power from the locomotive is typically not accessible to all wagons, alternative power sources such as batteries or power harvesting techniques must be used, and the device to be installed should have the lowest power consumption possible. The hardware must be capable of resisting the harsh railway environment, with varying levels of requirements based on its placement on the vehicle. To ensure an effective communication integration, technologies must be selected having the intention to be compatible with the linear network structure of trains. This can be achieved through various methods, including a direct wired connection, a wireless link to a hub on the locomotive, a node-to-node communication system (e.g., WSN), or a direct link to a remote Internet-connected hub.

As the IoT technology advances, the railway industry seeks innovative solutions to enhance efficiency, safety, and passenger experience. Similar to other sectors, the railway industry relies on efficient systems for optimal operation. The integration of tracking technology in trains plays a pivotal role in disaster prevention by calculating safe speeds on designated tracks, identifying obstacles, and enabling rerouting for enhanced safety. Furthermore, this technology aids in locating misplaced or malfunctioning rail cars, facilitating their timely removal from the train. Anticipated benefits include the introduction of new services like integrated security, asset management, and predictive maintenance, contributing to more informed decision-making for critical issues in the railway environment [11].

With challenges in accessing electric power, alternatives like batteries or power harvesting are crucial [12]. Communication integration necessitates technologies compatible with the linear train network, achievable through wired or wireless connections [13]. A 48-fiber telecom cable system is proposed for traffic monitoring [14]. WSNs offer flexibility and cost-effective deployment in railway applications [12]. GNSS for train positioning faces accuracy challenges as shown in [15] and [16]. Faults in WSN nodes and energy scarcity issues must be addressed for effective service [17], [18]. RFID, Zigbee, Sigfox, and LoRa are explored for varied applications, each with unique range and its own limitations [19], [20], [21], [22], [23]. LoRa's performance in suburban areas and under electromagnetic interference is assessed [24], [25]. The technologies ZigBee, Bluetooth, and Wi-Fi are the focus on identifying train composition alterations in [26]. Bidirectional communication using Bluetooth for high-speed scenarios is explored [27]. BLE proves effective for railway data transmission, with successful testing at 250 Km/h [28], [29]. In [30], it is studied the battery management and reliable communication in train wagon WSNs are achieved through accelerometer-driven sleep-wake cycles and optimized RF measurements. In [31], a robust WSN support system is proposed for freight train composition and integrity management, integrating GPS, IMU, UWB sensors, and received signal strength indicator (RSSI).

There are available solutions on the market used for assets tracking using different communication modules [32], [33], that are able to monitor in harsh environments and situations, retrieving the required data and position. Nevertheless, these solutions often work with licensed frequency bands communications, limited in terms of radio resources and have a high deployment cost. There are also projects such as Sensors4Rail of Digital Schiene Deutschland, that aims to collect environmental data and train position to interact with digital maps [34]. This project has established a system that needs a power supply across the whole transport, as it is required a high data rate for it.

The prevailing state-of-the-art in railway technology tends to prioritize advancements in machine learning and data analysis, potentially overshadowing the critical aspect of hardware integrity for onboard systems [35], [36], [37], [38], [39]. Despite this paradigm shift, it remains essential to also prioritize hardware development, emphasizing the need for a robust foundation alongside advancements in machine learning and related technologies.

III. COMMUNICATION SYSTEM

There are several options for communication technologies, and the best one for a particular project or application will depend on various factors. The deployment of a network may present significant challenges depending on the environment in which it is being used. Factors such as range, data rate,

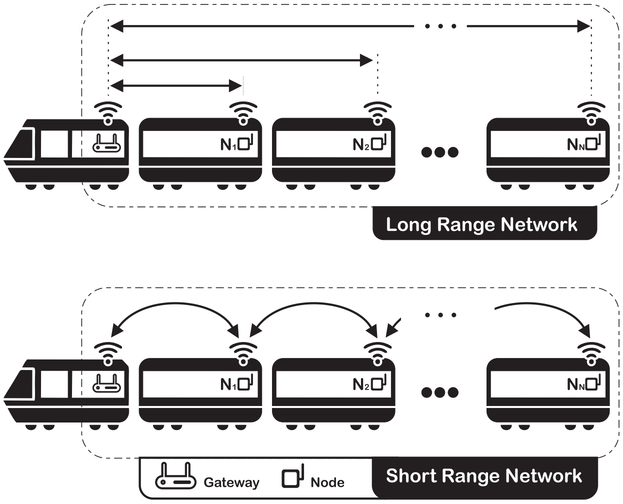


Fig. 1. WSN proposed for train monitoring.

frequency band, and power consumption must be considered when choosing a communication protocol.

A. System Requirements

The train shape and configuration originate a linear and almost even distributed WSN, where the locomotive is connected to the first train car and then to each subsequent car up to the last car; in Fig. 1, it is displayed that the nodes on the network should be able to communicate directly to the control center/gateway located on the engine wagon (long-range communication) and by relaying its message to its adjacent nodes, starting in the locomotive to the last wagon, hopping from node to node (short range communication).

The design the system takes into account the network node failures, the security of the network data, and reduce the power supply cost and maintenance (reducing and optimizing the network energy consumption).

Considering the points mentioned, it is expected that the WSN requires:

1) support monitoring of each node data, with a dynamic or prescheduled update time;
2) minimize node energy consumption (enabling low power mode);
3) decrease the maintenance cost of the network (extend battery duration);
4) can withstand individual failures, such as node or communication failures, and can easily handle nodes leaving or joining the network with minimal impact;
5) in case of not being able to reconnect to the network, the node should be able to communicate at a longer range of its current condition (including its position).

B. Short Range—Mesh Network

The chosen network for implementation in short range is BLE. It can be used as a communication technology for short to medium distances by implementing a mesh network. This topology is more complex but allows for the creation of large-scale device networks, and if it is considered the proposed system configuration in Fig. 1, the RF short-range communication will cover the range of a train car.

Each node sends and receives messages and can relay information received from any device to the destination device. This topology enables data to be obtained from an end node even if it is out of the range of direct communication, without resorting to center nodes like the star or cluster topologies.

The BLE mesh can support up to 32767 nodes in a network with a maximum of 126 hops for each message without any management. The Bluetooth mesh stack offers various configuration choices at different levels, ensuring reliability. BLE Mesh is based on the Bluetooth standard, widely adopted and supported by many devices. This makes it easy to integrate WSNs into existing systems and implement into devices if needed.

Another feature of this protocol is the managed flooding concept. Opposed to synchronous communication protocols that need to establish and maintain coincident node times, this mechanism allows the propagation of messages in the network using broadcast or to a group that the nodes are part of, enabling a message to be forwarded by several relay nodes. Depending on its configuration, the network nodes can rejoin the network and receive or even reply to messages by monitoring the communications [40].

Reviewing Fig. 1 the nodes are placed at each wagon edge, and the communication range between them can be defined by the transmission power and reception sensitivity. As this distance can be adjusted, it can be designed to guarantee the train integrity; if every node is given a different id that identifies the wagon and it is only within reach of its adjacent nodes, this protocol can recognize the nodes that respond to control center request and determine the current network elements. Some works explore different configurations to check the train integrity [41], [42], that can have single points of failure, such as relying on positioning the devices in a particular spot, and if it is disabled, it cannot connect to the next one. In [13] it is also defined as a system of four nodes per wagon connection to avoid single points of failure. However, it results in a more complex system and more devices for the network, not to mention more redundancy and a higher number of transmissions required.

C. Long Range—Direct Communication

In this work, at each train car is placed a network node that can only communicate through BLE to the adjacent cars nodes, where in case of unexpected points of failure along the network, there is the contingency of using the long-range communication for the control center try to communicate with the remaining cars, as illustrated in Fig. 2.

LoRa is a wireless communication technology that enables the data transfer over extended distances while consuming minimal power and bandwidth. It employs chirp spread spectrum (CSS) techniques, where the spreading factor regulates the data rate transmission by decreasing the number of chirps as it increases. LoRa operates in the free sub-GHz ISM

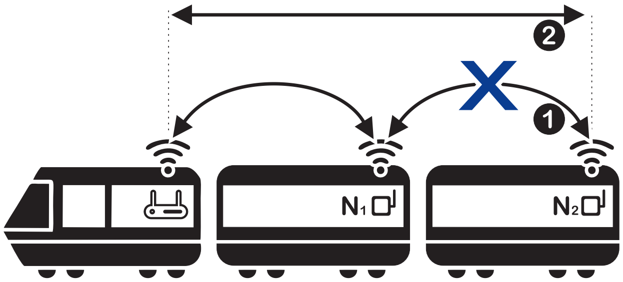


Fig. 2. Long range communication alternative contingency.

bands, which vary by region: Europe (433/868 MHz), America (915 MHz), and Asia (430 MHz). Its intended range for IoT applications is a few kilometers [24], [43].

For this work, LoRa is selected due to its long-range and reliable communication, its cost (especially when compared to technologies like cellular networks), and the compatibility with nowadays devices, enabling communications between train-to-ground and remote monitoring of equipment and infrastructures. Not to mention that LoRa uses encryption to secure communication and prevent unauthorized access. This is important in railway environments where sensitive data, such as train location and speed, needs to be protected.

Utilizing the capabilities of a BLE mesh network, nodes can communicate with one another when in range and relay data to nodes that are out of range. If a more extended communication or direct connection to a gateway is required, the nodes are to use LoRa technology to achieve it.

IV. SYSTEM ARCHITECTURE

Following the selected profile of communications, the system architecture is presented for this work.

A. Device Setup

Each node of the network is composed of different modules, which are shown in Fig. 3. The developed BLE node is constituted by a micro-controller unit (MCU) with Bluetooth enabled (ESP32) and an RFM95W LoRa modem, a temperature and humidity sensor DHT22, a GPS module (SAM-M8Q), and an antenna for the communications frequencies, supplied by a power bank. The selected MCU resources can support the WSN chosen communication protocols and application, while possessing the feature of entering low power modes [44], which can optimize the required energy for the device functioning. The Espressif provides an IoT development framework (ESP-IDF) to program the MCU. The module SAM-M8Q has an embedded wide-band patch antenna and high accuracy due to the reception of up to 3 GNSS (GPS, Galileo, GLONASS) [45].

With the goal of not only establishing the sensor network but also reducing the power needed to supply it, the connections and features among the elements of the system are analyzed; the sensors modules are peripherals of the MCU, which are directly connected in the case of low energy consumption of the DHT22, or connected with a compensation circuit for the case of high energy demand modules like the GPS module (even though that it has a low power mode, it still consumes energy).

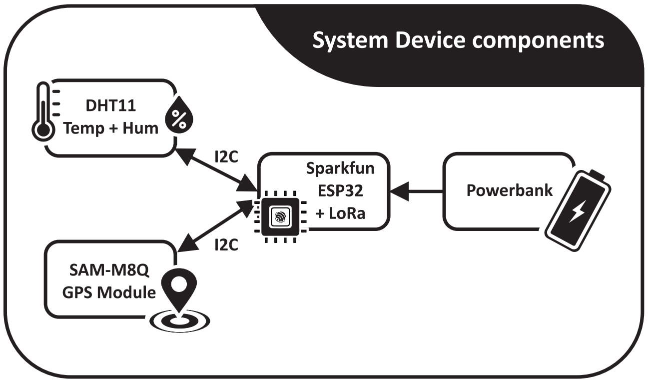


Fig. 3. Node device component composition.

After optimizing and consolidating the requirements for the WSN in terms of application and communication protocols, the next step should be to optimize the resources of the MCU for energy efficiency and cost-effectiveness.

As the table data shows, the GPS module power supply is, disregarding the MCU communication mode, the factor that demands more energy from the system. Usually, this type of high-consumption block has an enable button to save power, however, it still has some need of energy. To avoid that the modules consume energy when there is no request to update the sensors' data, the supply input of these modules is connected to MCU digital outputs and are only fed when an event triggers it. For the case of the GPS, this method does not provide enough current [45]. The resorted solution is to make a switch circuit that supplies the GPS module; the digital pin that should provide the power to the module is converted to an enable signal that can allow or inhibit the power supply to the GPS. This way, only when a request is made to identify the device's position, the GPS module is fed and activated. Fig. 4 displays the prototype for the design node.

B. Sensor Calibration

To validate the accuracy of data transmitted across the network, the DHT22 sensor underwent calibration within a climatic chamber. The calibration involved exposing the sensor to a controlled temperature range of −10 to 20 °C. This temperature range was selected based on the anticipated environmental conditions during the first field trials, providing a comprehensive assessment aligned with the initial expectations. Additionally, the calibration involved subjecting the sensor to a humidity range of 15%–95%. The chosen humidity range was carefully determined to account for the diverse humidity levels encountered in industrial settings. In industrial environments, humidity levels may vary widely, necessitating testing under both low humidity conditions and high humidity conditions. This approach considers the potential extremes that the sensor may encounter during its functioning. The

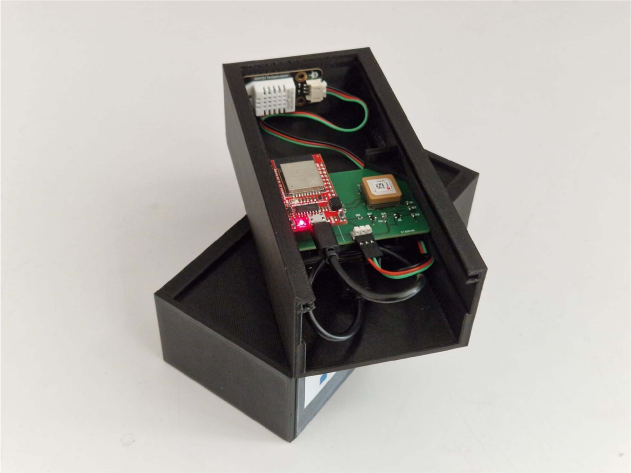


Fig. 4. Node device prototype for IoT system for train integrity and monitoring.

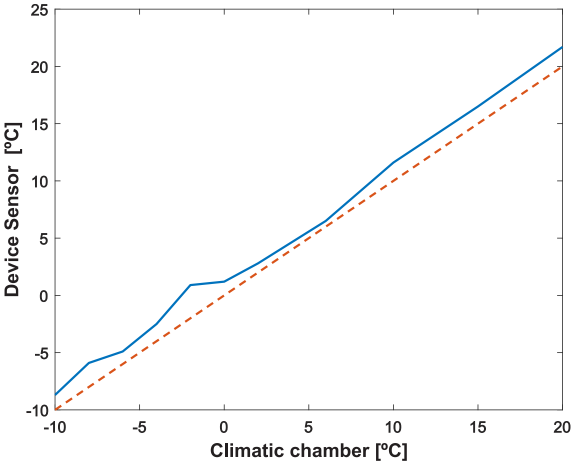


Fig. 5. Sensor calibration temperature comparison.

comparison between the results and the expected values are shown in Figs. 5 and 6.

With this calibration, it can be established a correction for the reading values and corroborated the results redeemed from the sensors in the next steps.

C. System Workflow

The system workflow is displayed in Fig. 7. To ensure that the device system is just using the energy when it is needed (data updates), the workflow is defined in two modes: low power mode and operating mode.

1) *Low Power Mode:* The device is economizing the energy consumption; the MCU enters in deep sleep mode, all the communication and sensor information retrieve blocks are disabled and an external event or timer is needed to awaken the CPU. The main memory is also disabled, where all the stored memory is erased and not accessible.
2) *Operating Mode:* The device checks the event that is responsible to awaken it and proceeds to execute the designated tasks. Depending on the process step, different modules can be active, including BLE and LoRa communications or the GPS.

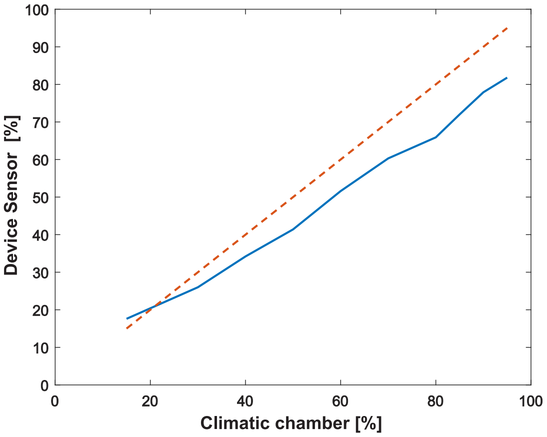


Fig. 6. Sensor calibration humidity comparison.

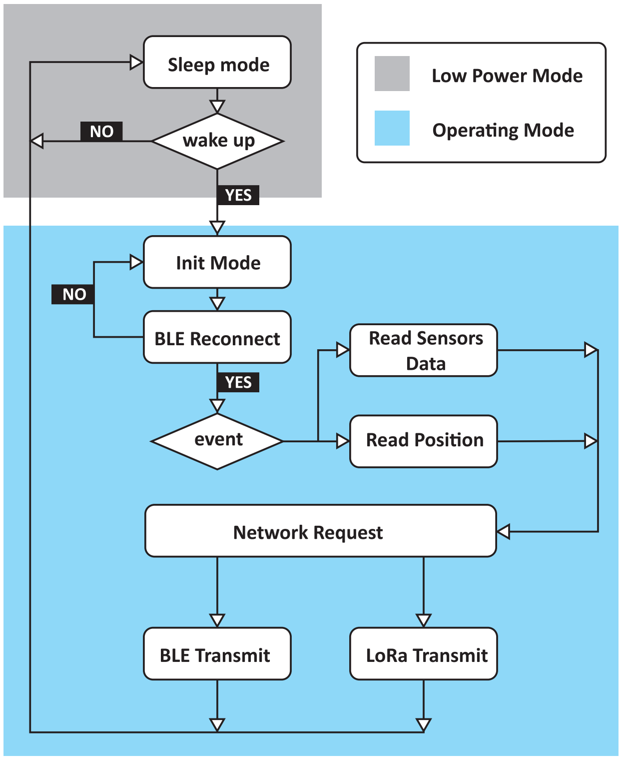


Fig. 7. System workflow.

In the low power mode, the power bank just supplies enough energy to make the ESP32 low power co-processor operate. It is designed to only leave this state if an external event (electrical signal) or a time event (prescheduled interruption) occurs along the device lifetime. As mentioned before, the BLE mesh requires that each node of the network has its credentials saved on its memory, and even though that the main memory is disabled, its configuration keys are stored away on the ESP32 secondary memory by using the software development kit. If it occurs one of the considered events, the system hops to the operating mode.

The first step on the awaken of the node is to restart the CPU processor of the MCU, enabling him to restart its normal functioning. After the reboot, the Bluetooth communication is reactivated and the device will use the saved network keys to be readmitted on the network. If it cannot reconnect to its mesh grid, the device returns to the reboot state and repeats the process until it can enter the network. After reconnecting, the micro-controller checks the event that has trigger the operating mode and attempts to give response to it. This gadget has two sensor modules that retrieve data (temperature + humidity and position), and the event identifies which update is requested. With the data retrieved from the designated sensor, the next step taken is review the event request to determine the type of communication to be used: short range and to the devices network placed in each wagon (BLE mesh) or long range and direct to the gateway (LoRa). When the data is transmitted, the node returns to the low power mode and waits for new event.

V. WSN IMPLEMENTATION AND TEST

Experimental results aim to check the viability of the designed WSN. It is analysed the nodes and network performance and energy consumption.

A. Node Performance

To configure a single node, it is tested its current consumption to the different stages of it. Before connecting and test the network functioning, the individual node is programmed to enter in different states:

1) *Low Power State:* The MCU is in deep sleep mode, with every module turned off, waiting for an awaken event.
2) *Short Range Communication Configuration State:* The device is provisioned to enter the BLE mesh network; it is given the credentials to enter and be accepted in the group. Process made once for configuration.
3) *Short Range Communication State:* The device reinitialize and reconnects to the BLE mesh network, relaying the data from the sensors to the network.
4) *Long Range Communication State:* The device turn on the GPS module to identify its position and after retrieve that information it activates the LoRa communication module and send its location data.

In Fig. 8 we can see the current necessary for the designated different states. The sleep mode shows a measure inferior to 1 mA (0.71 mA) while the BLE mesh communication event shows 110 mA. For the situation of long range communication and the GPS update information is needed, it reaches a peak of 144 mA. Note that in this state the GPS module has already performed a warm start to identify its position, making its acquisition in less time (∼5–10 s) than a cold start (∼25–40 s).

The experiment network performance can be separated into two parts: short range mesh network and long range network. To provision and configure the BLE mesh network nodes, it is used the smartphone app nRF Mesh.

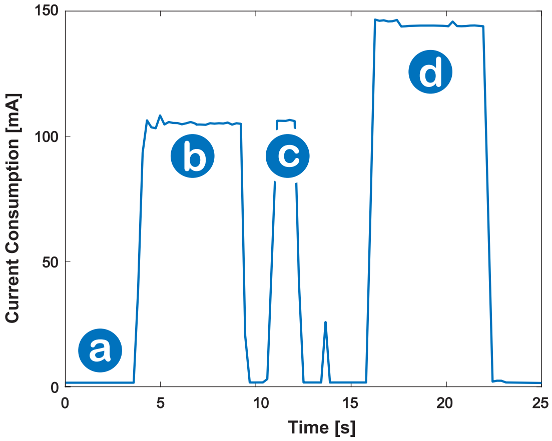


Fig. 8. Current consumption of a WSN node states.

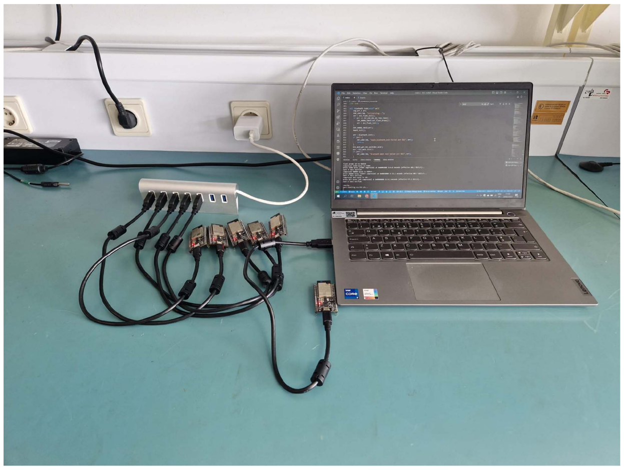


Fig. 9. WSN setup—direct connection to control center.

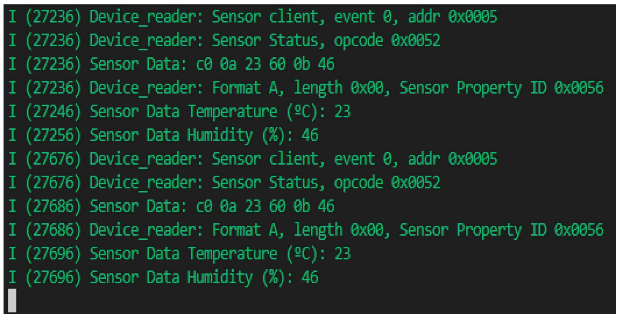
B. BLE Mesh Network Assessment

The first procedure is to analyse the performance of the WSN for the short range option, which verifies the train integrity.

The necessary data to be retrieved from each node doesn't require high bit rates like applications of image or video streaming, which makes it possible to balance the communication data rate and energy consumption. For the experimental setup, it is expected the monitoring of the temperature and humidity from each node, where the data is sent to the network group upon request received. The data hops from node to node until it reaches the gateway. The train integrity is defined by the reach of the messages of each car to the control center, as each train car only has a network reach limited to the adjacent nodes.

In a first phase, the nodes are tested in a controlled environment, close to each other as seen in Fig. 9.

After configuring the nodes, one of them is connected to the laptop in order to simulate the control center. It is programmed to request the temperature and humidity level data of every device present on the defined group. The nodes that are authenticated with the application and network keys (safeguarding the integrity and confidentiality of the



```
I (27236) Device_reader: Sensor client, event 0, addr 0x0005
I (27236) Device_reader: Sensor Status, opcode 0x0052
I (27236) Sensor Data: c0 0a 23 60 0b 46
I (27236) Device_reader: Format A, length 0x00, Sensor Property ID 0x0056
I (27246) Sensor Data Temperature (ºC): 23
I (27256) Sensor Data Humidity (%): 46
I (27676) Device_reader: Sensor client, event 0, addr 0x0005
I (27676) Device_reader: Sensor Status, opcode 0x0052
I (27686) Sensor Data: c0 0a 23 60 0b 46
I (27686) Device_reader: Format A, length 0x00, Sensor Property ID 0x0056
I (27696) Sensor Data Temperature (ºC): 23
I (27696) Sensor Data Humidity (%): 46
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Fig. 10. WSN setup—direct connection to control center results.

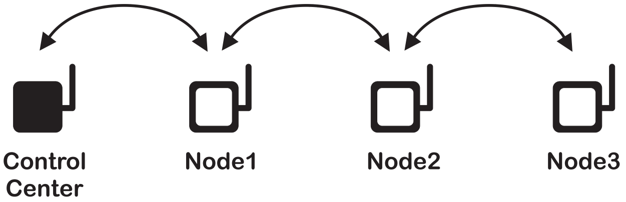


Fig. 11. WSN setup—relay BLE mesh feature.

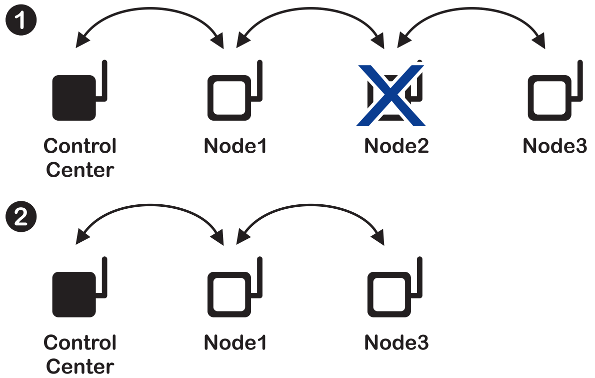
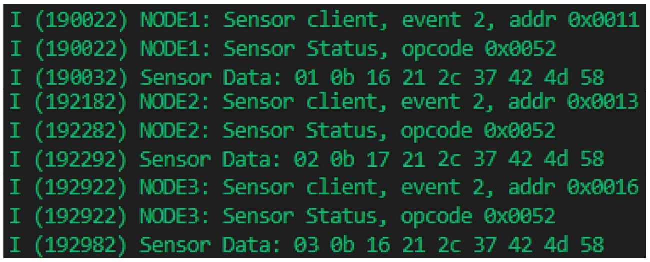


Fig. 12. WSN setup—reconfiguration BLE mesh feature setup.

data exchanged among nodes) are enabled to listen to the request trigger a response and send the requested values to the group, that reach the control center as expected, showing the results of it in Fig. 10. It is displayed an example of the data collected (the octet units and the resultant data in form of string) from different nodes addresses in the control center.

The next step is to configure and test the relay feature of the BLE mesh network, as it is a vital point of the network functioning. Fig. 11 shows the scheme for this test, where the devices are placed in a range that they can only communicate with the adjacent ones, which means the mid node needs to relay the information between both neighbor nodes.

The last test for the short range communication is the ability to reconfigure the network chain, as shown in Fig. 12. In the train composition, the wagons order and number are flexible and may be altered during the trip at different stops. To make up for that situations the BLE mesh used enables an alternative routing when an element is missing. In this case is tested the removal of one of the mid relay nodes and adjusted the others places to be within the network range, to see if the remaining elements still can communicate despite the unit withdrawal.



```
I (190022) NODE1: Sensor client, event 2, addr 0x0011
I (190022) NODE1: Sensor Status, opcode 0x0052
I (190032) Sensor Data: 01 0b 16 21 2c 37 42 4d 58
I (192182) NODE2: Sensor client, event 2, addr 0x0013
I (192282) NODE2: Sensor Status, opcode 0x0052
I (192292) Sensor Data: 02 0b 17 21 2c 37 42 4d 58
I (192922) NODE3: Sensor client, event 2, addr 0x0016
I (192922) NODE3: Sensor Status, opcode 0x0052
I (192982) Sensor Data: 03 0b 16 21 2c 37 42 4d 58
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Fig. 13. WSN setup—relay BLE mesh feature results (collected from control center).

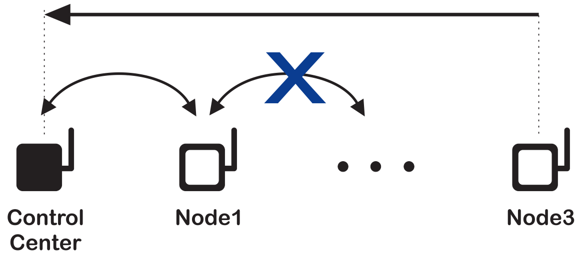


Fig. 14. LoRa setup.

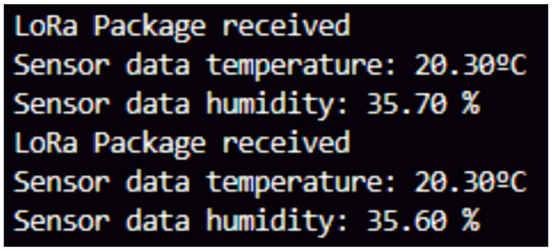
The results show that the communication hop feature enables the communication of the network, even though that there is no direct connection between the control center and the more distant node, even in case of a required reconfiguration of the network elements. Fig. 13 shows the obtained serial monitor of the control center, displaying data received from different addresses. The nodes within the BLE mesh network are enabled to maintain message buffers or queues to store data temporarily. The messages are queued until the node is back online or the reconfiguration is completed for the nodes that are still not back online.

C. Long Range Assessment

The BLE mesh solves the train integrity and it can be used to communicate with all the nodes, resorting to hop the data among them. However there is also a need to communicate if the device cannot reestablish the connection to the network. Due to the reasons posted formerly, the devices incorporate a LoRa technology module to cover this issue, where the position of the device that cannot reconnect to the Bluetooth network after a defined number of tries is broadcasted via LoRa.

Similar to the prior setups, a node is placed linked to the laptop simulating the control center, while other node is out of range for the BLE network connection, as shown in Fig. 14.

Due to the code programmed on the MCU, after 3 tries to reconnect to the mesh network fail the device will turn on the GPS position and after acquiring its location will send it via LoRa. Fig. 15 shows the message received by the control center after the event, while Fig. 16 shows the current consumption during this process.



```
LoRa Package received
Sensor data temperature: 20.30ºC
Sensor data humidity: 35.70 %
LoRa Package received
Sensor data temperature: 20.30ºC
Sensor data humidity: 35.60 %
```

Fig. 15. LoRa setup results (collected from control center).

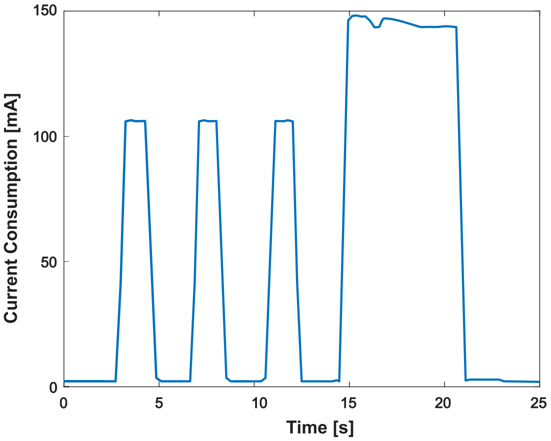


Fig. 16. LoRa setup current consumption.

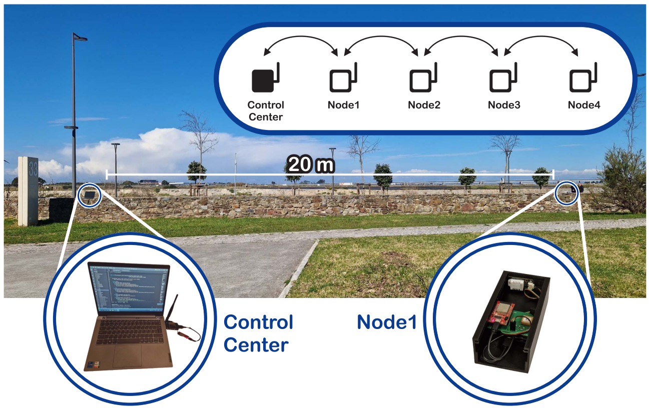
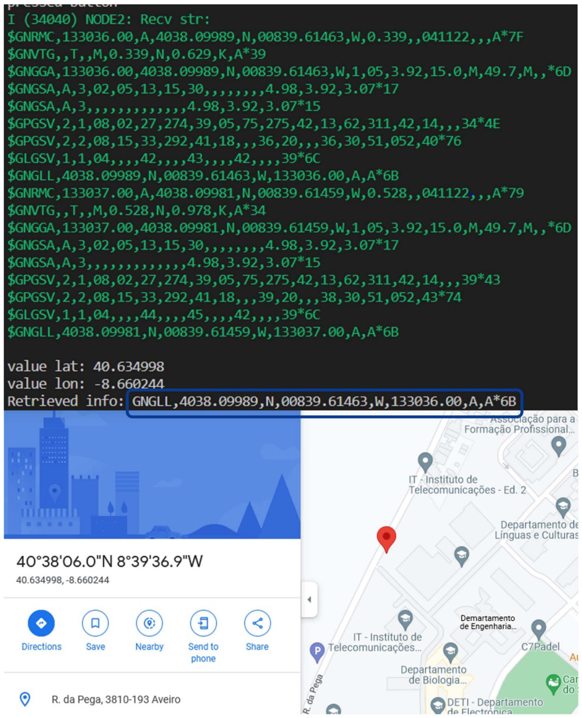


Fig. 17. WSN setup—outdoor tests.

D. WSN Field Setup 1

After the previous steps, the first field setup is to integrate the two types of communication in a field test. For validation purposes, it is used a smaller scale model network composed by 5 nodes, covering the connection between four train cars and the locomotive, being this last one simulating the gateway and monitored by being connected to a laptop. For emulating similar train propagation conditions were made outdoor tests.

The setup is displayed in Fig. 17. The first nodes are separated for 20 m apart (common train car length), placed on the wall, able to connect to the network. The last node is placed further in order to severe the link between this node and the BLE mesh network and activate the location event via LoRa.



```
I (34040) NODE2: Recv str:
$GNRMC,133036.00,A,4038.09989,N,00839.61463,W,0.339,,041122,,,A*7F
$GNVTG,,T,,M,0.339,N,0.629,K,A*39
$GNGGA,133036.00,4038.09989,N,00839.61463,W,1,05,3.92,15.0,M,49.7,M,,*6D
$GNGSA,A,3,02,05,13,15,30,,,,,,,,4.98,3.92,3.07*17
$GNGSA,A,3,,,,,,,,,,,,,4.98,3.92,3.07*15
$GPGSV,2,1,08,02,27,274,39,05,75,275,42,13,62,311,42,14,,,34*4E
$GPGSV,2,2,08,15,33,292,41,18,,,36,20,,,36,30,51,052,40*76
$GLGSV,1,1,04,,,,42,,,,43,,,,42,,,,39*6C
$GNGLL,4038.09989,N,00839.61463,W,133036.00,A,A*6B
$GNRMC,133037.00,A,4038.09981,N,00839.61459,W,0.528,,041122,,,A*79
$GNVTG,,T,,M,0.528,N,0.978,K,A*34
$GNGGA,133037.00,4038.09981,N,00839.61459,W,1,05,3.92,15.0,M,49.7,M,,*6D
$GNGSA,A,3,02,05,13,15,30,,,,,,,,4.98,3.92,3.07*17
$GNGSA,A,3,,,,,,,,,,,,,4.98,3.92,3.07*15
$GPGSV,2,1,08,02,27,274,39,05,75,275,42,13,62,311,42,14,,,39*43
$GPGSV,2,2,08,15,33,292,41,18,,,39,20,,,38,30,51,052,43*74
$GLGSV,1,1,04,,,,44,,,,45,,,,42,,,,39*6C
$GNGLL,4038.09981,N,00839.61459,W,133037.00,A,A*6B

value lat: 40.634998
value lon: -8.660244
Retrieved info: GNGLL,4038.09989,N,00839.61463,W,133036.00,A,A*6B
```

Fig. 18. Retrieving position after reconnect BLE mesh network failure.

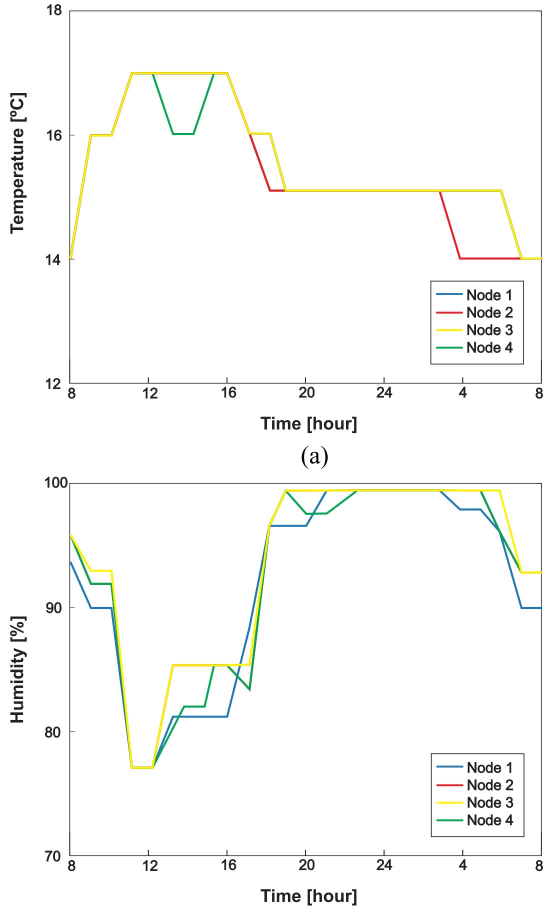
The results show that the nodes within range can still enter the network and update the requested data. The node outside the network was not able to connect with the remaining devices, and after trying reconnect without achieving it, the GPS module was mobilized and transmitted its position over LoRa communication. Fig. 18 shows the information received by the control center as well the location retrieved.

After establishing the different states and reviewing the performance of each feature defined on the system, it is made an analysis of its power consumption and the sensor data retrieving for the nodes on the network over a day, with an update rate of 30 min. Every 3 h the node would also activate its contingency mode and transmit its location via LoRa. The sensor data is presented on Fig. 19, corroborating the previous success trials connection outcome. With the designed life cycle, the power consumption has an average power consumption of 2.4 mAh.

E. WSN Field Setup 2—Train

The final setup is placed on a train composition, as detailed in previous sections of this study and present on Fig. 20. The devices that compose the system were placed on each wagon, covering the first four chain elements of the train. The transmission power of each device is risen to be able to cover 30 m.

The implementation of the IoT system on a real train composition encountered some challenges, including the proper location for each device and some signal mitigation which results on a need for a higher transmitting power. However, operationally wise, there were no problems concerning the system communication. Using the same experiment as before, the system worked when applied to a train composition. The



(a)

(b)

Fig. 19. Sensor data output of WSN nodes. (a) Temperature sensor node data. (b) Humidity sensor node data.

Fig. 20. WSN setup—outdoor train composition test.

(a)

(b)

Fig. 21. Field Setup for the train integrity and monitoring system test. (a) Network Nodes placed along the train composition. (b) Network Control Center over the draisine.

results show that the communication is still enabled, where the control center receives the data from the other nodes.

Tests were also conducted in a test railway line to emulate propagation conditions similar to those of a moving train. The experimental setup is shown in Fig. 21. Devices are placed on each available rail car of the draisine, preconfigured to access the local BLE mesh network. The coverage is limited to a distance of 15 m to prevent direct communication between all devices and the control center. The test consists of two phases: the first tests the Bluetooth network to assess the integrity of the moving rail vehicle, and in a subsequent phase, the contingency plan is triggered in case of a disappearance of a BLE network element. The last railcar is positioned farther away, preventing it from establishing a connection with the rest of the BLE mesh network and triggering the location event via LoRa. The prototype system's results validate the proposed Virtual Coupling, as the applied WSN recognizes and triggers a protocol when the mentioned event occurs, sending necessary identification information to the control center.

In terms of latency, the esp32 has a limit as low as 7.5 ms per transmission [44], however this is for the Bluetooth direct communication between two esp32 devices. In this work, the control center has to send its data update request to the mesh network address so that all devices connected to it can relay its data. To analyze the system's latency, it was made a program where it saves the timestamps for the control center request

TABLE I
LATENCY RESULTS FROM FIELD SETUP

Trial	Update Request [ms]	Control-N1 [ms]	Control-N2 [ms]	Control-N3 [ms]	Control-N4 [ms]
1	170	+42	+52	+47	+54
2	162	+51	+48	+41	+61
3	183	+60	+44	+46	+41
4	177	+55	+47	+43	+58
5	174	+46	+51	+42	+46
6	168	+56	+42	+49	+53
7	166	+53	+42	+54	+48
8	169	+51	+47	+41	+53
9	172	+48	+51	+43	+64
10	168	+47	+57	+51	+43

LPM - Low Power Mode

TABLE II
STATE OF THE ART COMPARISON

<table>
<tr><th>Work</th><th>Comm. Type</th><th>LPM | AM [mA]</th><th>Fallback Measures</th><th>Authentication</th><th>Latency [s]</th></tr>
<tr><td>This</td><td>BLE mesh</td><td>0.7 | 144</td><td>LoRa + GPS</td><td>Yes</td><td>2.63</td></tr>
<tr><td>[13]</td><td>Sub-GHz</td><td>1.0 | 30</td><td>Backup Nodes</td><td>No</td><td>3.6</td></tr>
<tr><td>[16]</td><td>Wi-Fi</td><td>- | -</td><td>GPS</td><td>No</td><td>30-200</td></tr>
<tr><td>[30]</td><td>BLE</td><td>- | -</td><td>Backup Nodes</td><td>Yes</td><td>30-200</td></tr>
<tr><td>Wired</td><td>Wire</td><td>- | -</td><td>No</td><td>No</td><td>-</td></tr>
</table>

and the time it receives the info from the other nodes. In Table I it is displayed the latency results obtained, showing the time delay that occurs until the control center receives the data from each node for several trials. Analyzing the table, it can be infer that the update request from the control node to the network takes an average time of 170.1 ms and each node adds a mean latency time of 49.2 ms. Considering a composition of 50 wagons, the average time it would take to get an update of all the carriage operating, confirming the train integrity, would be 2.63 s. A suitable interval for reporting the train integrity is generally considered to be no longer than every 5 s [46], meaning that the proposed solution can be seen as fit for this criteria.

In Table II is displayed the comparison between this work and the state of the art. Comparing to solutions with GNSS-based systems, these consume a higher amount of energy or have a need for a higher time of targeting its location (50-200 s) [15], [16]. The work in [13] has also no need for external infrastructures and has a 3.6s period to identify the train integrity, however this work shows a lower latency and it may overhear and communicate fewer packets in the last nodes of the composition. Additionally, it lacks an authentication system to secure its network. In [30] the nodes are placed on each wagon, with redundant backups using BLE, although the focus is to implement a sleep cycle to the nodes and the power consumption nor the latency are not presented. There are also other approaches that use wired networking on cars that can be more reliable, however are not ready to be implemented at older train models and present wiring costs for its integration. Conversely, the system of this article can be easy configured and placed in each wagon of the train composition without further wire installments.

VI. CONCLUSION

In this work it was designed a reconfigurable IoT solution to monitor and check the train integrity and applied in a real train composition. The system consists on a WSN that enables the communication between the nodes via BLE mesh, relaying update data requests from the control center to the end car wagon. In case of disconnection and not able to reconnect, the device has a LoRa transmission contingency of its positioning. Each element of the network has an MCU able to retrieve and process information as the application requires. The power consumption has an average of 2.4 mAh for an hourly update situation, with a current utilization less than 1 mA (0.7 mA) in sleep mode, with the integrity of a 50 node model train can be reported in an average time of 2.63 s. The results show that the communication resources are resilient to network reconfigurations and single point fails, being able to locate the device at long distances.

The proposed WSN needs enhancements to improve its energy efficiency and reliability, along with its security and node prototype design. In terms of energy efficient, it is possible to create a PCB where it is placed the same MCU and remove some elements that have a higher consumption and are consuming power even in sleep mode (e.g., voltage regulators, USB interface), and implement energy harvesting modules and a power management unit with it. Its reliability can be further increased by tailoring the transmitting power for each wagon, so that the integrity of the train is more rigorous. The security can be improved by changing the network room address from time to time. The current node prototype design is of a considerable size due to the power bank, however it could be redesigned to be more compact and its fixating mechanism also needs to be designed. The WSN parameters and code can be optimized depending on the application. The implementation of wake up radio can avoid redundant sensor readings due to timer interrupts unnecessary or even establish updates on demand, and the system should be tested over long distances covered by the train composition.

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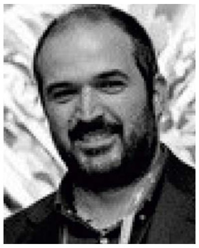

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