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An end-to-end Internet of Things solution for Reverse Supply Chain Management in Industry 4.0

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ABSTRACT

The recent increase in the number of products returned from customers to retailers, supported by the adoption of environment-friendly policies, has led to a growing need to manage backward materials and information flows in the supply chain (SC) domain. Although numerous authors are contributing towards circular economy (CE) with end-of-life (EoL) approaches minimizing the negative impact of Waste Electric and Electronic Equipment (WEEE), the information infrastructure behind SC calls for novel approaches based on Information and Communication Technologies (ICT). In fact, this is one of the major challenges for the so-called Industry 4.0, where wireless technologies governed by the Internet of Things (IoT) are expected to transform the industry as currently conceived. The present work proposes an end-to-end solution for Reverse Supply Chain Management (R-SCM) based on cooperation between different IoT communication standards, enabling cloud-based inventory monitoring of WEEE through embedded sensors. A case study was deployed using IoT devices and sensors, carrying out a set of experimental tests focused on wireless communications to evaluate its performance. The network configuration adopted overcomes the near real-time challenge and provides sufficient coverage to interconnect industrial areas such as warehouses or shop floors. The results point to different communication bottlenecks that need to be addressed in order to enhance the reliability of large-scale Industrial IoT (IIoT) networks.

1. Introduction

The circular economy (CE) is motivated by an increasing need to minimize the economic and environmental impact of end-of-life (EoL) products [1]. This industrial strategy refers to the long-lasting design, refurbishment, remanufacture, repair, recycling or reuse of products in order to achieve the maximum benefit and avoid negative impacts, with Waste Electrical and Electronic Equipment (WEEE) being a growing concern [2]. According to the United Nations University (UNU), 44.7 million metric tonnes of e-waste was generated in 2016, with future estimations being even larger [3]. While posing significant risks for the environmental and human health, it contains recoverable raw materials with an estimated value of 55 billion euros.

Reverse logistics (RL) has become a key competence of both the supply chain (SC) and reverse supply chain (RSC) [4,5], in which products flow from customers to manufacturers. Reverse Supply Chain Management (R-SCM) emerges as a new challenge, given the necessity of managing every single stage where products should be handled and distributed towards manufacturers, with multiple recovery options increasing the uncertainties faced by companies [6].

The introduction of Information and Communication Technologies (ICT) in SC and, especially, the Internet of Things (IoT) can significantly improve process-oriented performance, reduce energy consumption and provide SC with a ubiquitous information infrastructure [7]. By enabling the cooperation of wireless technologies, IoT is an accelerator of the Fourth Industrial Revolution: Industry 4.0 [8,9]. This brand-new concept is transforming the industrial paradigm, being Cyber-Physical Systems (CPS), cloud and fog computing essential pillars [10,11]. The impact of IoT on industries is such that the concept of Industrial IoT (IIoT) is becoming increasingly popular and has consequently been adopted in several industrial applications governed by IoT technologies [12].

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Nomenclature

AWS	Amazon Web Services
BW	Bandwidth
BLE	Bluetooth Low Energy
CE	Circular economy
CR	Coding rate
CPS	Cyber Physical Systems
DR	Data rate
DSC	Digital supply chain
EoL	End of life
ETSI	European Telecommunications Standards Institute
IIoT	Industrial Internet of Things
ICT	Information and Communication Technology
IT	Information Technology
IoT	Internet of Things
JSON	JavaScript Object Notation
LoRaWAN	Long-range wide-area network
LPWA	Low-Power Wide-Area
MQTT	Message Queing Telemetry Transport
RFID	Radio-Frequency IDentification
RSSI	Received signal strength indicator
RL	Reverse logistics
RSC	Reverse supply chain
R-SCM	Reverse Supply Chain Management
SNR	Signal-to-noise ratio
SBC	Single-board computer
SF	Spreading factor
STD	Standard deviation
SC	Supply chain
SCM	Supply chain management
TTN	The Things Network
UNU	United Nations University
WEEE	Waste Electric and Electronic Equipment

Despite the large body of literature addressing IoT applications in the supply chain management (SCM) domain, the RSC field specifically needs more integrated approaches based on IoT communication standards to manage the RL of WEEE in real contexts. To fill this gap in the literature, this paper presents a novel Industry 4.0 end-to-end IoT framework as a solution for WEEE management.

The following aspects of this work can be highlighted. First, the proposal of a heterogeneous IoT network enabling low-power and low-cost SCM operations in the context of Industry 4.0. For this, we propose the cooperation of three emerging IoT technologies for R-SCM, presenting a case study based on the recovery of WEEE from computer-based components. Second, the implementation of an end-to-end system, addressing the deployment of sensor-nodes, the network infrastructure, and its integration with a cloud-based inventory-management platform. In order to evaluate end-to-end performance, a set of experimental tests are proposed, carried out and discussed.

The three wireless technologies selected and addressed in this work are RFID [13], Bluetooth Low Energy (BLE) [14] and LoRaWAN [15], which are tested under different communication schemes and physical-layer parameters. Our results illustrate the suitability of the proposed IoT standards for R-SCM purposes, underlining communication optimizations for large-scale industrial deployments.

The paper is organized as follows: in Section 2 we review the literature; the IoT framework for R-SCM is presented in Section 3; Section 4 presents a WEEE-focused case study; Section 5 addresses the experiments, results and discussion; and finally, Section 6 provides conclusions and identifies future research lines.

2. Related works

This section provides a review of the most relevant works and applications of computer-based systems in the industrial sector, highlighting the main contributions and gaps that encourage us to propose and evaluate an end-to-end heterogeneous IoT framework for R-SCM purposes.

2.1. Circular economy

The principles of CE were first outlined by Kneese et al. [16] dealing with the management of residuals and the improvement of environmental quality. Recently, its scope has been broadened to not only involve the minimization of natural resources but also the ability to reuse materials [17]. Currently, resources are mined, turned into products and finally discarded [18]. As a result, our society is generating scarcity, volatility, unaffordable manufacturing costs and, what is more worrying, an unprecedented absence of natural resources [19]. According to Vella [20], *a shift towards a circular economy could bring savings of €600bn for EU businesses, and reduce greenhouse gas emissions by 2–4% every year*, which highlights the necessity of adopting CE strategies.

In this context, WEEE is receiving special attention, being one of the fastest-growing waste streams with a 33% increase in volume reported during the last five years [21]. The roots of this increase are connected with exponentially-growing consumer demand, technology uptake, and shorter replacement cycles. Moreover, the adoption of free-shipping policies on part of most companies has accelerated electronic commerce, where the product-return ratio has risen to 30%, more than three times that of brick and mortar sales [22].

In the European Union, e-waste is regulated by the Directive 2012/19/EU of the European Parliament and Council [23]. According to a recent communication, in 2015 only four European Union Member States recycled over half of the electronic products put on the market [24]. This is supported by Eurostat [25], which published a report concluding that the lowest recycling rate of waste streams corresponds to e-waste (32%) followed by plastics (40%). In fact, 44.7 million metric tonnes of e-waste was generated globally in 2016, with an annual growth rate up to 5% on a weight basis [3]. Apart from the need to mitigate environmental pollution, the economic value associated with raw materials present in such e-waste is estimated at 55 billion euros [3].

In pursuit of a reduction of waste streams through an environment-friendly and cost-saving approach, remanufacturing has become one of the most feasible EoL strategies to restore products to ‘like-new’ condition. If well-organized and planned, it can expand the life-cycle of products and increase profits of manufacturing companies through reducing landfills [26]. Despite being under-recognized in the current industrial landscape, remanufacturing generated 29.8 billion euros in turnover and 192,000 employment in the European Union in the year 2015, with expectations of attaining an annual value of 100 billion euros in 2030 [27].

As part of the European Research Framework H2020, the European Remanufacturing Network has facilitated the development of sustainable partnerships between organizations, similarly to the ResCoM (Resource Conservative Manufacturing) initiative and its successor ReCiPS (Resource-Efficient Circular Product-Service-Systems).

In this context, information-sharing capabilities enable cooperation among suppliers, manufacturers and recyclers, being necessary to take responsibility for the collection, disposal and recovery of products at their EoL [28]. In the literature, Garcia-Muiña et al. [29] explore the transition stages towards circularity and propose a theoretical ICT-based framework where materials are sourced to manufacturers following a CE model. A similar approach is provided by Asif et al. [30], who design an ICT framework for information-sharing in pursue of a product-as-a-service model in the washing-machine industry. Finally, Gu et al. [31] provide a theoretical IoT framework for WEEE management but lacking ICT details and practical implementations.

None of these works focus on using IoT technologies to address information flows being exchanged upwards the SC or evaluate the performance of communications, which we believe is a necessary condition. Our work, additionally, focuses on WEEE and provides a detailed framework describing the handling stages of products from their EoL stage to their reuse in a R-SCM context.

2.2. Digital supply chain

The SCM strategic objectives have been widely defined in the literature as *cost*, *quality*, *speed*, *flexibility* and *dependability* [32–34]. During recent years, *sustainability* has gained special interest, with insufficient communication capabilities being a major obstacle to its adoption [35]. In this context, a number of SC information-infrastructure requirements have emerged, namely: *flexibility*, *cost*, *time*, *quality*, *accuracy*, *reliability*, *visibility* and *availability* [36,37].

The digital supply chain (DSC) is thus a growing area of research interest, calling for innovative approaches based on emergent technologies to manage SC processes. Its major challenges were recently defined by Büyüközkan and Göçer [38], converging in: *speed* (ability to react quickly to demand), *flexibility* (agile reaction), *global connectivity* (internet-enabled SC), *real-time inventory* (continuous monitoring of stocks levels), *intelligence* (self-learning smart products), *cost-effectiveness* (use of technology to increase organizational performance), *transparency* (adjusting networks to changing scenarios), *scalability* (optimization and duplication of processes), *innovation* (in pursue of competitiveness and excellence), *proactivity* (anticipating issues prior to occurrence) and *eco-friendly* (environmental emphasis).

Information and material flows need to be managed efficiently in downstream and upstream directions [18,39,2]. The main differences between forward and reverse SCs lie in *distribution channels* (standardized vs. exception-driven), *transparency* (asset-tracking information available vs. poor asset visibility) and *timing requirements* (time-critical vs. non-time-critical), among others [40].

2.3. The role of IoT in the Fourth Industrial Revolution

IoT, a term first coined by Ashton [41] with regard to SCM, provides physical objects – or *Things* – with sensing and ubiquitous communication capabilities. Despite being initially conceived for customer-oriented applications, the latest advances have enabled a broader scope for IoT, permitting the integration of sensors in industrial facilities, equipment and resources towards the so-called IIoT [42,43]. In this context, the Fourth Industrial Revolution – or Industry 4.0 [44] – emerged incorporating CPS into traditional factories governed by IIoT, which promises great advances [45,46].

Several authors provide IoT approaches to wireless communications [47]. The BLE standard has been widely studied from energy-efficiency [48,49] and low-latency [50] perspectives. Rondón et al. [51] provide an in-depth evaluation of BLE, supporting its suitability for time-critical industrial applications. Likewise, the performance of the LoRaWAN standard was studied by Sanchez-Iborra et al. [52]; important studies also exist on improving capacity [53] and communication performance [54,55].

Hofmann and Rüsch [56] regard *real-time information flows*, *end-to-end transparency* and *flexibility* as three key objectives of Industry 4.0, whereas Büyüközkan and Göçer [38] highlight the necessity of integrating sensor networks in heterogeneous environments towards this goal. Nevertheless, there is great disparity across countries in terms of Industry 4.0 adoption, which is a potential barrier to advancement [57]. Two major areas of research are highlighted based on the gaps that our work aims to fill in the Industry 4.0 field: heterogeneous approaches based on wireless technologies collaboration and end-to-end applications oriented towards specific use cases.

As heterogeneous approaches, Gioia et al. [58] present an IoT gateway integrating multiple sensors, buses and technologies, while Garrido-Hidlago et al. [59] describe the implementation of a hybrid network to improve working conditions in industry through the use of industrial wearables [60]. Regarding end-to-end applications, Tao and Qi [61] propose an IT-driven framework towards smart manufacturing. In the domain of SCM, Abdel-Basset et al. [62] present a framework for IoT-enabled securely-efficient systems, Papert and Pflaum [63] define an ecosystem to encourage IoT services in the domain of SCM and Wakenshaw [64] presents an IoT integration framework.

Table 1 provides a comparison of the most representative works in our literature review. Many of these studies address descriptive approaches or simulations, whereas others focus on the experimental evaluation of a single IoT standard lacking of an end-to-end perspective or industry-oriented deployment concerning a heterogeneous IoT ecosystem. We fill this gap in the literature proposing and testing a real end-to-end IoT solution based on a heterogeneous network proposal for R-SCM of WEEE.

3. IoT framework for R-SCM

This section describes an IoT R-SCM framework proposal to manage WEEE, aimed at providing manufacturers with a novel ubiquitous information infrastructure behind SC for tracking of parts to be recovered. For this, we first select the set of IoT standards for the deployment (based on a communication-range criterion) and, then, the main stages of the framework are described according to their functionality and information flows.

Our proposed IoT-based WEEE management framework is supported by a twofold approach: on the one hand, the presentation of an industrial solution to contribute to filling a real gap of WEEE management across SC and, on the other, the provision of an IoT network architecture to connect SC with a transparent inventory-management infrastructure in the context of Industry 4.0.

3.1. Selection of IoT standards

The proposed R-SCM framework distinguishes between three sets of IoT standards according to their communication range: short-range, intermediate-range and long-range. MQTT [66] was selected for data transmission between physical devices (IoT network deployed in the facilities) and virtual data infrastructures (inventory cloud platform), while a unique standard was selected from each set to fulfill the framework requirements:

Short-range communication. We selected high-frequency RFID [13] over NFC [67] for the identification of returned products in the framework. Despite being popular for contactless payment, information sharing and user-oriented applications, NFC is not suitable for industrial use. High and ultra-high frequency RFID offer robustness against metal interference and a greater communication range (typically in the order of tens of meters).

Intermediate-range communication. BLE [14] was selected over Wi-Fi [68] or ZigBee [69] for local data transmission and inventory management in the framework. Although operating in the same frequency bands, BLE is oriented toward IoT applications where the volume of information to be sent is small and low power is encouraged, having become a disruptive standard for Industrial IoT applications.

Table 1
Comparison of the main contributions found in the literature.

Source	Method						Scope or domain area					End-to-end ICT infrastructure					Heterogeneous IoT network			
	Descriptive	Theoretical	Case study	Simulation	Implementation	Experimental	Industry 4.0	Internet of Things	Circular economy	Reverse logistics	WEEE	Framework	Perception layer	Network layer	Application layer	Performance test	RFID-based	BLE-based	LoRaWAN-based	IP-based
Abdel-Basset et al. [62]						√		√		√		√					√			√
Asif et al. [30]					√				√			√			√					√
Cattani et al. [54]					√	√							√	√	√	√			√	
Cho et al. [50]		√		√												√		√		
Cuomo et al. [55]		√		√												√			√	
Dementyev et al. [49]						√								√		√		√		
Garcia-Muiña et al. [29]			√				√		√			√	√							√
Garrido-Hidalgo et al. [59]					√	√	√						√	√	√	√		√	√	√
Genovese et al. [17]			√						√	√										
Gioia et al. [58]	√				√			√					√	√						
Gu et al. [31]	√		√					√		√	√	√					√			
Papert and Pflaum [63]	√							√	√			√								
Roda-Sanchez et al. [60]					√	√	√						√	√		√		√		
Rondón et al. [51]		√		√			√									√		√		
Sanchez-Iborra et al. [52]						√										√			√	
Siekkinen et al. [48]						√		√					√	√		√		√		
Tao et al. [65]	√						√					√								√
Wakenshaw [64]	√						√	√				√								
Yang et al. [28]					√					√	√	√		√	√		√			√
Zorbas et al. [53]		√		√												√			√	
Our work			√		√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√

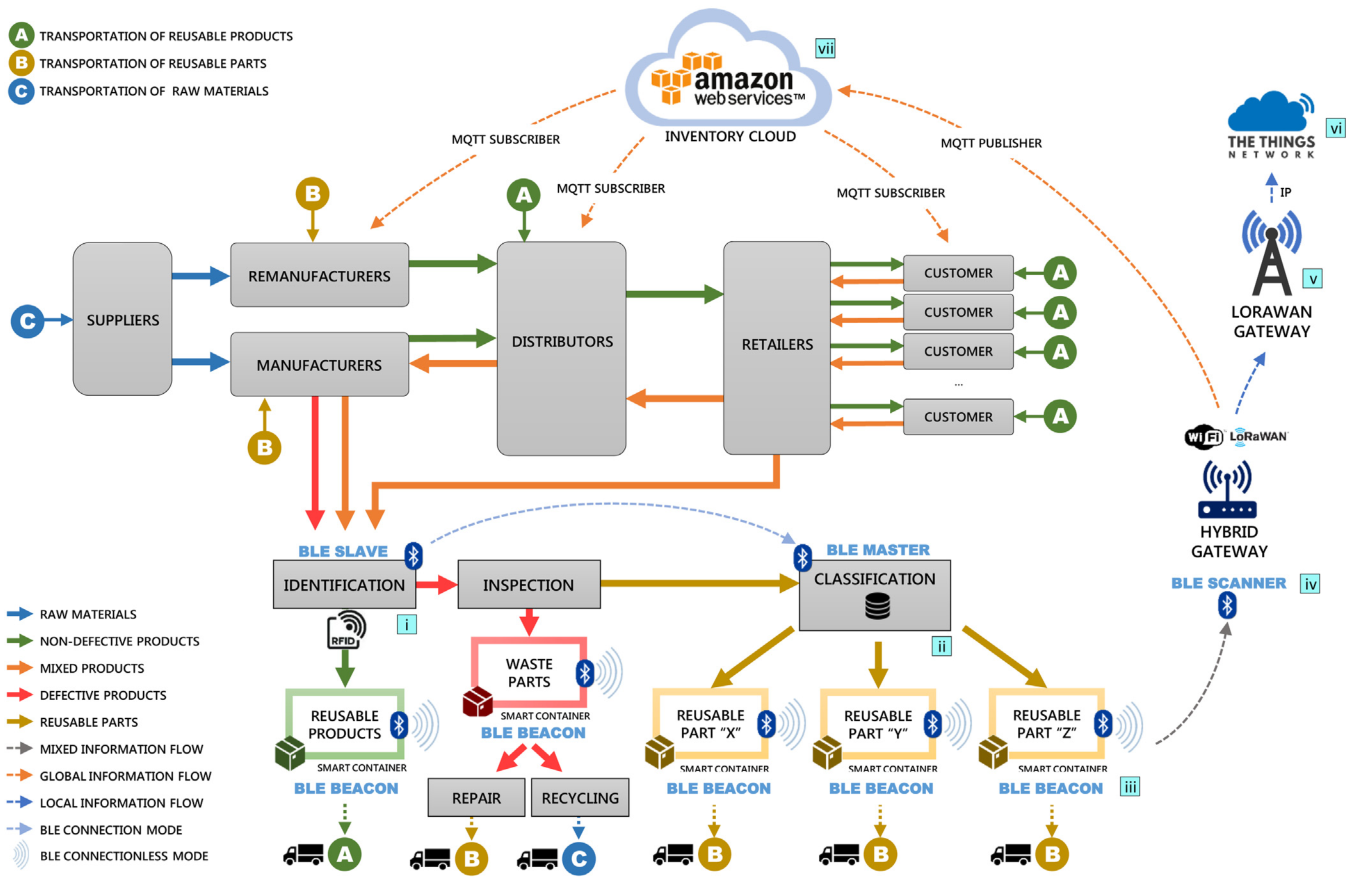


Fig. 1. R-SCM IoT framework based on: Identification Stage (i), Classification Stage (ii), Smart Containers (iii), Hybrid Gateway (iv), LoRaWAN Gateway (v), TTN (vi), AWS (vii).

Long-range communication. Regarding Low-Power Wide-Area (LPWA) standards, LoRaWAN [70] was selected over NB-IoT [71] or Sigfox [72] for environmental monitoring of assets and interconnection of industrial facilities. The main advantages of NB-IoT and Sigfox technologies lie in their narrowband implementation providing robustness against noise and, specifically, Sigfox has the lowest chip cost and NB-IoT the lowest network latencies. However, LoRaWAN is the best choice for bidirectional communication and provides more flexibility, enabling firmware upgrades over-the-air, a unique feature of this technology oriented toward large-scale IoT deployments. Furthermore, LoRaWAN provides better robustness against mobility, which we regard as an essential requirement for SC scenarios.

3.2. Description of the stages

The proposed framework offers end-to-end IoT integration combining physical devices and sensors, wireless communications (RFID, BLE and LoRaWAN) and platforms for data storage and analytics. Fig. 1 shows the framework, the main components of which are the Identification Stage, Inspection Stage, Classification Stage, Smart Containers and Hybrid Gateway.

This work is aimed at deploying the communications infrastructure able to manage data gathered during the recovery of WEEE, with the Inspection Stage being outside the scope of the concerned network. Nevertheless, this stage is responsible for the disassembly of products and the refurbishment of modular components to ensure that they meet the necessary conditions for reuse. Non-recoverable components are sent to repair or recycling plants depending on their deterioration. Once reusable parts are classified into separate containers, the Hybrid Gateway is responsible for collecting data and managing two flows of information: global (inventory updates) and local (environmental information).

Table 2
IoT standards used (classified as input or output).

Framework stage		Input standards	Output standards
(i)	Identification Stage	RFID	BLE 4.0
(ii)	Classification Stage	BLE 4.2	None
(iii)	Smart Containers	None	BLE 4.0
(iv)	Hybrid Gateway	BLE 4.2	LoRaWAN, MQTT
(v)	LoRaWAN Gateway	LoRaWAN	IP
(vi)	TTN	IP	None
(vii)	AWS IoT Core	MQTT	MQTT

Table 2 summarizes the compliance with IoT standards: the Identification Stage (i) combines RFID technology to scan tagged products with BLE to forward the information to the Classification Stage (ii), received via BLE 4.2. The Smart Containers (iii) use BLE to update inventory and environmental information, which is received by the Hybrid Gateway (iv) and respectively forwarded through the LoRaWAN Gateway (v) to The Things Network [73], TTN (vi) or via MQTT to IoT Core platform in Amazon Web Services [74], AWS (vii).

Identification Stage (i). The aim of this stage is to read information written on RFID tags to identify the reason of return and the other key aspects of products. Tags are expected to be attached by the retailers or manufacturers shipping the EoL products, and written according to an agreed data-encryption algorithm – as, for example, the one proposed by ElMahgoub [75] – in order to control data access and simplify the identification of products entering the system. Once read, an actuator system would intro-

Classification procedure and communication

```
product_type ← characteristic UUID for subset (i.e. laptop)
part_type ← characteristic UUID(s) for part model(s) information
if data in product_type characteristic then
    for all data in part_type do
        if data ∈ database and data ∉ tmp then
            tmp ← data associated to part model
            weight ← weight of current part
            match weight with internal database of weights
            container ← match position found
            pop tmp
        else if data ∉ database and data ∉ tmp then
            tmp ← data associated to part model
            weight ← weight of current part
            push weight onto tmp_object
            information ← information associated to part
            push information onto tmp_object
            push tmp_object onto database
            pop tmp
        end if
    end for
end if
```

Fig. 2. Algorithm used for classification and communication.

duce reusable products into containers and let defective products continue through the system. At the Identification Stage the device is provided with RFID and BLE modules. Once the RFID tags are scanned, this device (under the *slave* BLE role) exchanges information with its *master* (Classification Stage).

Classification Stage (ii). This stage is the core of the framework, where information about products and parts is collected. The parts received at this stage will have passed a quality control test, and are thus assumed to be reusable. The device located in this stage acts as BLE *master* and receives information from the previous stage by discovering the *services* and reading the *characteristics* of the *slave* (according to the BLE specification in Bluetooth SIG [14]). The Classification Stage includes a database where standard part models are stored to access information such as reference models, kind of product or weight. Subsequently, the device weighs parts to classify them. Fig. 2 provides a detailed description of the classification algorithm, where $product_{type}$ refers to a product *subset* (kind of product, i.e. laptop or desktop computer) and $part_{type}$ to the specific models of the parts stored with additional information in a JSON file.

Smart Containers (iii). These devices integrate a microcontroller platform, a load cell and an accelerometer, being able to communicate via BLE under the BLE *advertiser* role to update inventory and context information. This stage is designed to weigh parts and calculate the available number of parts of each type to be reused, turning containers into useful real-time platforms. Every time acceleration suffers a significant change, an interruption event wakes up the microcontroller and measures weight: if it has changed, it will recalculate the number of items (according to the type of parts inside each container) and send a packet via BLE (see Fig. 2).

Hybrid Gateway (iv). This device is intended to collect information emitted by BLE *advertisers*, the Smart Containers, (for which it assumes the role of *scanner*) and classify it according to a local/global criterion. Two kinds of information flows are created in the Hybrid Gateway (see Fig. 1):

- *Local information flow*. This information is generated in Smart Containers when something unexpected occurs (i.e. low battery level of devices) and is sent to the Hybrid Gateway. This device is responsible for encapsulating this context data, adding sensed ambient information, and sending it through a LoRaWAN gateway (v) to TTN (vi).

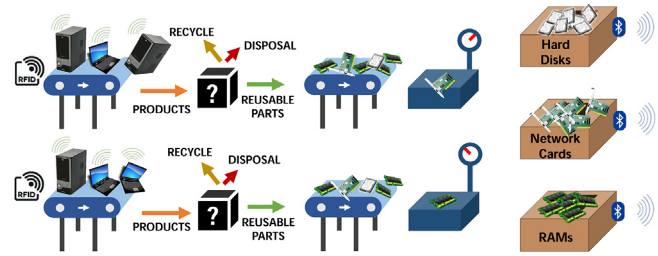


Fig. 3. Disassembly stages: Identification (i), Classification (ii) and Smart Containers (iii).

- *Global information flow*. This consists of inventory data updated by Smart Containers. The Hybrid Gateway, acting as a BLE *scanner*, receives a mixed information flow, filters it and publishes inventory updates via MQTT in AWS IoT Core (vii). Once data is stored in AWS, any authorized entity could subscribe to get immediate inventory updates.

4. Case study

Personal computers have become one of the major concerns regarding waste-streams generation, given a considerable decrease in their average useful life over the years and a high environmental impact associated with their disposal. Nevertheless, most components found in computers are in good condition for reuse or refurbishment and, depending on their added value, these can be brought back to the required degree of quality as presented in [26].

Following this idea, the scenario selected for the case study was an industrial environment focused on the recovery of computer-based products. Fig. 3 represents the flow of products and parts throughout the stages of the system in our case study scenario.

The two subsets of products used in the experiments were desktop and laptop computers, which entered the system being identified via RFID. Then, products would be sent to the Inspection Stage, where the appropriate EoL strategy would be applied according to their added value and condition (outside the scope of the case study). For classification, we used components disassembled from damaged computers, which are shown in Table 3, in addition to their approximate cost and main specifications used by the classification algorithm (see Fig. 2).

The case study consisted in the identification and classification of components using sensors and communication modules, which were attached to the microcontroller-based platforms deployed throughout the R-SCM system. The implementation and deployment of a real hardware prototype permitted the evaluation of IoT communications taking place in the end-to-end system.

The single-board computers (SBC), sensors and radio communication modules used to deploy the prototype are shown in Table 4. LightBlue Bean as an implementation of the ATmega 328P microcontroller with the LBM313 BLE radio was used for Identification Stage (i) and Smart Containers (iv); LoPy as an implementation of Xtensa LX6 including the BLE/Wi-Fi ESP32 and the LoRa SX1276 radio module was used to develop the Hybrid Gateway; a Raspberry Pi 2B based on the BCM2836 microprocessor was used to deploy the LoRaWAN gateway (on the roof of the testing building); a Raspberry Pi Zero W based on the BCM2835 and the CYW43438 BLE radio was used for the Classification Stage. Additionally, we attached two type of sensors to LightBlue Bean: load cells and ambient sensors, specifically, three two-kilogram straight load cells and Pysense to test the proposal using the temperature-and-humidity integrated sensor Si7006-A20. Regarding radio modules, the RC522 RFID communication module was included at the Identification Stage, operating at high-frequency (13.56 MHz) and the iC880A LoRaWAN concentrator (integrating the SX1301 transceiver) with an external 868 MHz

Table 3
Specifications of WEEE parts used in the experiments.

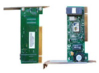
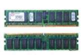
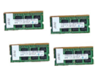
WEEE	Part type	Part model	Subset	Weight (g)	Cost (€)
	Hard disk	ST31000340AS	*Desktop*	642	90
	Network card	HE-012D	*Desktop*	60	10
	Network card	FT16-04B3	*Desktop*	55	15
	Network card	GTS FC-515	*Desktop*	56	9
	Graphic card	QUADRO FX-580	*Desktop*	220	139
	RAM	KTM2865-SR	*Desktop*	18	17
	RAM	CF81037	*Laptop*	8	40

Table 4
Hardware used in the deployment (radio specifications are marked as input$^{(i)}$ or output$^{(o)}$ information flows).

Framework stage	Core	Sensors	Radio modules
(i) Identification Stage	ATmega 328P	None	MFRC522$^{(i)}$, LBM313$^{(o)}$
(ii) Classification Stage	BCM2835	TAL 220	CYW43438$^{(i/o)}$
(iii) Smart Containers	ATmega 328P	TAL 220	LBM313$^{(o)}$
(iv) Hybrid Gateway	Xtensa LX6	Si7006-A20	ESP32$^{(i/o)}$, SX1276$^{(o)}$
(v) LoRaWAN Gateway	BCM2836	None	SX1301$^{(i)}$, Ethernet$^{(o)}$

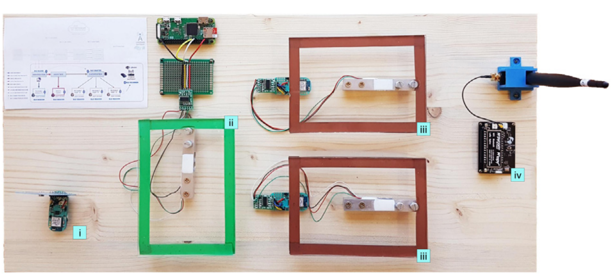


Fig. 4. Prototype developed for evaluation of the R-SCM framework, showing: Identification Stage (i), Classification Stage (ii), Smart Containers (iii) and Hybrid Gateway (iv).

antenna was used for the LoRaWAN gateway deployment (located outdoors, on the roof of the Albacete Research Institute of Informatics).

All the materials (except the LoRaWAN gateway) were distributed and screwed to a wooden board in order to implement a low-cost prototype that permitted us to test the communication performance of the different standards. Fig. 4 shows the resulting prototype.

5. Results and discussion

The experiments were designed to satisfy a set of performance tests to assess the strengths and limitations of the R-SCM proposal under IoT criteria [76]. These tests are described in Table 5 and scaled according to real-world experiments with IoT devices instead of simulations.

The $T_{N_{SC}}$ metric quantifies the influence of increasing Smart Containers on latency (BLE standard); T_{OA} the Time-on-Air at LoRaWAN end-devices as a function of payload, complying with ETSI [77] regulations of 1% duty cycle, N_{PCK}; T_1, T_2, T_3 provide a disaggregated end-to-end communication latency considering the cooperation of all technologies; RSSI (received signal strength indicator) and SNR (signal-to-noise ratio) determine the signal quality perceived at the LoRaWAN Gateway depending on end-device location.

Table 6 showcases the setup of the experiments, where G_a is the antenna gain, P_{tx} the transmission power and S_{rx} the receiver sensitivity. The conditions for the Geographic Spread experiments were cloudless skies and temperatures from 26 to 30 °C, in Albacete, Spain. The height of the transmitting end-device was 2 meters, and the height of the LoRaWAN gateway 18 m. The LoRaWAN specification [15] provides further information on physical-layer parameters: spreading factor (SF), coding rate (CR), data rate (DR) and bandwidth (BW); and the BLE specification [14] provides more details on the main network roles used in this work, namely: *scanner/advertiser* in broadcasting mode and *master/slave* in connection mode.

5.1. Data ingest test

A scaled system would imply the addition of new lines with incoming products and, thus, the increase of BLE traffic received by the Hybrid Gateway and forwarded via MQTT to AWS. Whereas the former could become a potential bottleneck for the system, the latter has been widely tested in the literature with no apparent scalability limitations for IoT, reaching up to 263,314 packets received and 23,184 sent per hour under a 0% packet loss [78].

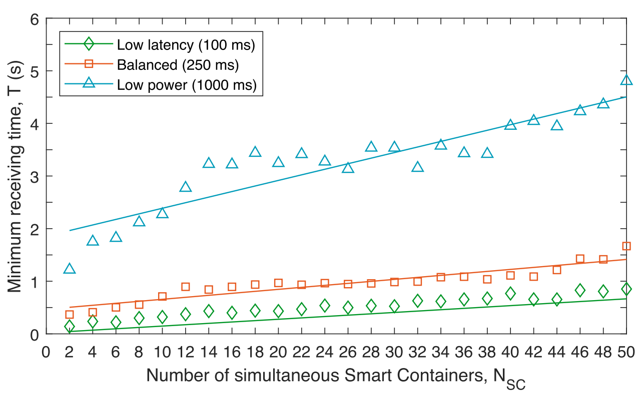
A series of BLE-based experiments was carried out to evaluate the influence of increasing the number of Smart Containers, updating inventory information to a same Hybrid Gateway. For this, the NRF Connect [79] software was used to ingest BLE traffic in the network and measure the resulting $T_{N_{SC}}$. Each experi-

Table 5
IoT-oriented tests to evaluate the prototype.

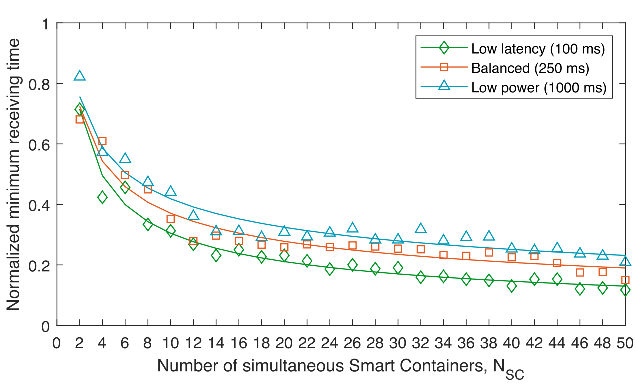
Stages involved	Test	Description	Metrics
(iii), (iv)	Data ingest	Influence of traffic on performance	$T_{N_{SC}}$
(iv), (v)	Data size	Influence of payload on performance	T_{OA}, N_{PCK}
(i) → (iv), (vii)	Network latency	Disaggregated end-to-end performance	T_1, T_2, T_3
(iv), (v)	Geographic spread	Influence of distance on signal quality	RSSI, SNR

Table 6
Experiments setup: parameters and IoT standards specifications in the R-SCM solution.

Parameter	RFID	Bluetooth low energy (BLE)			LoRaWAN	
Role	Reader	Master/Slave	Advertiser	Scanner	End-device	Gateway
Frequency	13.56 MHz	2.4 GHz	2.4 GHz	2.4 GHz	868 MHz	868 MHz
Modulation	ASK	GFSK	GFSK	PSK	LoRa	LoRa
Radiation	Directional	Directional	Omnidirectional	Omnidirectional	Omnidirectional	Omnidirectional
G_a (dBi)	–	–	1.7	–	3	8
P_{tx} (dBm)	Variable	8.5	3	7.5	14	14
S_{rx} (dBm)	–	−97	−93	−98	–	−136/−120



(a) Minimum receiving time at Hybrid Gateway ($T_{N_{SC}}$).



(b) Normalized minimum receiving time at Hybrid Gateway ($\hat{T}_{N_{SC}}$).

Fig. 5. Influence of the increase of Smart Containers N_{SC} in the minimum receiving time ($T_{N_{SC}}$) for BLE advertising intervals of 100, 250 and 1000 ms.

ment was carried out ten times increasing traffic conditions under low-power (1000-ms advertising), balanced (250 ms) and low-latency (100 ms) configurations. The resulting average is shown in Fig. 5a.

The results provided in Fig. 5a highlight the communication time required in case of simultaneous transmission attempts on the part of Smart Containers. Fig. 5b provides the normalized minimum receiving time of the Hybrid Gateway for a given number of Smart Containers, obtained as the inverse of the minimum receiving time divided by the advertising interval. Eqs. (1) to (3) provide the tendency lines and curves obtained from the experiment data:

$$\begin{cases} T_{N_{SC(100\text{ms})}} = 0.0129 \times N_{SC} + 0.0183 & R^2 = 0.9547 \\ \hat{T}_{N_{SC(100\text{ms})}} = 1.0323 \times N_{SC}^{-0.530} & R^2 = 0.9687 \end{cases} \quad (1)$$

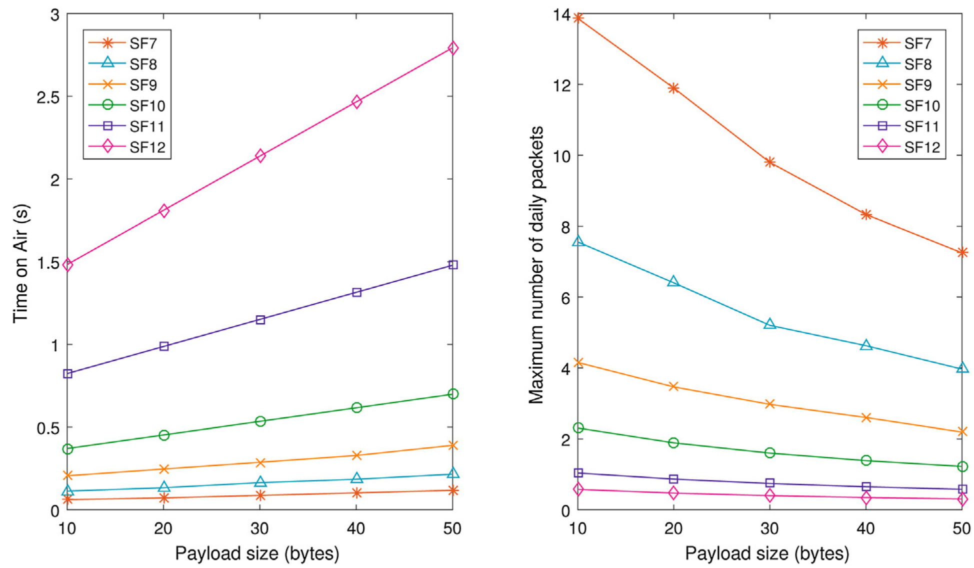
$$\begin{cases} T_{N_{SC(250\text{ms})}} = 0.0189 \times N_{SC} + 0.4669 & R^2 = 0.8551 \\ \hat{T}_{N_{SC(250\text{ms})}} = 0.9663 \times N_{SC}^{-0.416} & R^2 = 0.9206 \end{cases} \quad (2)$$

$$\begin{cases} T_{N_{SC(1000\text{ms})}} = 0.0529 \times N_{SC} + 1.8576 & R^2 = 0.8326 \\ \hat{T}_{N_{SC(1000\text{ms})}} = 0.9766 \times N_{SC}^{-0.368} & R^2 = 0.9285 \end{cases} \quad (3)$$

The advertising interval implies the reception of one packet of each container every 100 ms for a low-latency configuration, 250 ms for balanced and 1000 ms for low power. However, as the number of Smart Containers increases, we observe in the results how the proportional time required to receive a single packet also increases (see Fig. 5a). Let us consider the low-power configuration as an example: with devices advertising every 1000 ms, the ideal $T_{N_{SC}}$ would be 1000 ms, but experimentally ranges from 2000 to 4500 depending on N_{SC}.

If different advertising intervals are considered for the same N_{SC}, taking into account Fig. 5b, important conclusions are reached. Let us consider the worst-case scenario with 50 containers transmitting simultaneously ($N_{SC} = 50$): for a low-latency configuration, the ideal $T_{N_{SC}}$, 100 ms, is up to 10 times lower than the experimental one (nearly 1000 ms according to Fig. 5a), whereas for a low-power configuration this value is approximately 5 times lower than the expected (1000 ms ideally with respect to the nearly 5000 ms reached experimentally). This can be observed in Fig. 5b, where the normalized minimum receiving time ($\hat{T}_{N_{SC}}$) for a low-power configuration is two times that of low-latency.

Thus, despite the low-power configuration having a worse absolute latency, the normalized results show that in this case the effectiveness of transmissions is the highest. This means that the proportion of packets lost during communication increases with the number of containers (N_{SC}) and also with the reduction of the advertising interval. The origin of the problem may be related to collisions taking place when the BLE traffic in the network is increased (either augmenting the transmitting frequency or the number of devices in the network). Further research is required to assess the origin of this packet loss in pursuit of more efficient large-scale industrial networks.



(a) Influence of payload in T_{OA}.

(b) Influence payload in N_{PCK}.

Fig. 6. Influence of LoRaWAN end-devices packet size (CR of 4/5, BW of 125 kHz and different SF) in T_{OA} and N_{PCK} for a 1% duty cycle.

5.2. Data size test

This test focuses on the LoRaWAN network, since the performance of LPWA is significantly influenced by variable data payloads. In contrast to the data ingest test, where scalability implied a scenario with increased traffic, this experiment aimed to highlight the required Time-on-Air (T_{OA} metric in Table 5) of LoRaWAN end-devices for different configurations and volumes of data.

Following the standard [15], the LoRa physical layer uses several *chips* to encode each symbol, resulting in SF configurations ranging typically from SF7 (2^7 chips/symbol) to SF12 (2^{12} chips/symbol). In order to calculate the Time-on-Air required when setting different SFs, the symbol duration (T_{sym}) should be defined as shown in Eq. (4):

$$T_{sym} = \frac{2^{SF}}{BW} \tag{4}$$

Eq. (5) provides the formula to obtain the T_{OA} metric (see [80] design guide). The *payloadSymbNb* was computed considering the presence of a header. The preamble duration was obtained according to Eq. (6) as a function of the symbol duration (T_{sym}) and the number of preamble symbols ($n_{preamble}$) and, then, the packet duration was obtained according to Eq. (7) as a function of the symbol duration (T_{sym}) and the number of header and payload symbols (*payloadSymbNb*):

$$T_{OA} = T_{preamble} + T_{header+payload} \tag{5}$$

$$T_{preamble} = T_{sym} \times (4.25 + n_{preamble}) \tag{6}$$

$$T_{header+payload} = T_{sym} \times payloadSymbNb \tag{7}$$

Fig. 6a shows the required T_{OA} for 10-to-50-byte payloads for different SF configurations. The results range from approximately 70 ms to 2.8 s. Although, the number of LoRaWAN end-devices used for the experiments was not sufficiently large to involve communication bottlenecks in the R-SCM approach proposed, the results of this test are useful to focus on a further industry-oriented scalability of the system.

For large-scale deployments, the coexistence of several LoRa devices transmitting under the same SF configuration involves significant probability of failed transmissions due to intra-SF collisions (collisions occurring when two devices transmit at the same time, using the same frequency band and SF). Additionally, inter-collisions can also be noticed when the same frequency band is shared but different SFs are set up, although this is less likely to occur [53]. In view of the T_{OA} results obtained, high SF configurations and long payloads should be avoided, when possible, in order to reduce the probability of collisions caused by a long channel-occupancy time.

The results are useful to determine the maximum number of LoRa-based transmissions permitted for any end-device according to 1% duty cycle regulations (see ETSI [77] for further documentation). Fig. 6b provides a useful approximation, based on the results from Fig. 6a. Let us consider a 20-byte payload configured under SF10 as an example: in this case, ETSI would limit an end-device to transmitting, at most, 2000 packets per day (more than sufficient for environmental monitoring in distributed warehouses). However, TTN restrictions of 30 s of T_{OA} per device and day [81] applied to Fig. 6a results would only permit 60 packets in the previous situation. For this reason, further research is required to use alternative self-deployed network servers to enhance the framework flexibility.

5.3. Network latency test

This test quantified stage-to-stage and end-to-end latencies of the inventory-management functionality of the system for a given configuration, since the local functionality (LoRaWAN-based) was tested in depth in Section 5.2. The metrics used to provide the results are T_1, T_2 and T_3 (see Table 5), which correspond to those represented in the sequence diagram in Fig. 7. This experiment provides an overall latency approach based on the cooperation of RFID, BLE and MQTT standards, with all BLE devices being programmed with advertising intervals of 100 ms.

In Fig. 7, T_1 refers to the time elapsed from when a new product is identified via RFID and metadata is sent via BLE to Classification Stage, until the acknowledgement is received. T_2 refers to the time elapsed from when a new part is noticed in a Smart Container until the BLE advertisement packet containing the inventory update reaches the Hybrid Gateway. Finally, T_3 is the time

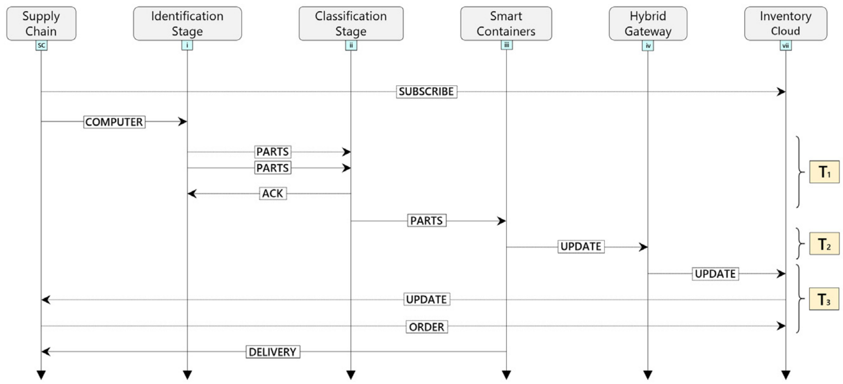


Fig. 7. Sequence diagram of the inventory-management system (T_1, T_2 and T_3 metrics).

Table 7
Results of the network latency test (in ms).

Metric	Average	Maximum	Minimum	STD	Stages involved
T_1	185.530	214.184	166.960	23.220	(i), (ii)
T_2	124.635	170.744	117.920	18.631	(iii), (iv)
T_3	65.724	69.909	62.106	2.457	(iv), (vii)

elapsed between an inventory update being received via BLE and a client subscribed via MQTT to the topic-of-interest receiving the notification.

The measured latency of the end-to-end system is shown in Table 7, according to metrics T_1, T_2 and T_3. The experimental results show T_1 and T_2 are significantly higher than T_3, which means that no communication constraints or bottlenecks might be noticed when scaling MQTT connectivity with the AWS IoT platform. Metrics T_1 and T_2 should be analyzed according to the communication standards and industrial process associated with each one.

If we consider the inspection of components between the RFID-based identification of products and the classification of parts (see Fig. 1), an average latency of approximately 185 ms, T_1, would not limit the performance of the R-SCM system. Conversely, our results point to the fact that T_2, the BLE link between Smart Containers and their Hybrid Gateway, could limit the speed of the system if latencies of all stages are compared. Nevertheless, an overall minimum delay of 124 ms would not limit the inventory-monitoring functionality of the system, especially considering the requirements associated with the RL purpose of the system [40].

5.4. Geographic spread test

This test evaluates LoRaWAN coverage based on RSSI and SNR (see Table 5) using the TTN Mapper [82] tool. Fig. 8 shows a map of the city of Albacete (Spain), the scenario used for the experiments. The gateway is represented by a cross and end-device positions (P) into equidistant circles.

Table 8 shows and interprets the results. Since the receiver sensitivity and, consequently, the minimum SNR is different per SF, the SNR results in Table 8 should only be compared in columns.

Since RSSI and SNR should not be considered absolute values, Eqs. (8)a to (8)f simplify our *quality* (Q) interpretation criteria. Given the implementation of transceivers [83], when the signal is sufficiently strong, it is attenuated avoiding overload. RSSI and SNR are obtained after attenuation, which is why SNR values equal or higher than 5 dB have been attenuated. In such cases, only RSSI provides relevant information (the lower its absolute value, the better). Otherwise, the minimum SNR threshold supported (−7.5 dB for SF7, −10 dB for SF8, etc.) is considered to calculate a margin:

$$
Q = \begin{cases}
\checkmark\checkmark\checkmark & \text{SNR} \geq 5\ \text{dB}\ \textit{and}\ \text{RSSI} \geq -100\ \text{dBm} & \text{(8a)} \\
\checkmark\checkmark & \text{SNR} \geq 5\ \text{dB}\ \textit{and}\ \text{RSSI} < -100\ \text{dBm} & \text{(8b)} \\
\checkmark & |\text{SNR}_{min} - \text{SNR}| \geq 5\ \text{dB} & \text{(8c)} \\
\text{✗} & 5\ \text{dB} > |\text{SNR}_{min} - \text{SNR}| \geq 2\ \text{dB} & \text{(8d)} \\
\text{✗✗} & |\text{SNR}_{min} - \text{SNR}| < 2\ \text{dB} & \text{(8e)} \\
\text{✗✗✗} & \text{otherwise} & \text{(8f)}
\end{cases} \tag{8}
$$

The influence of vegetation is noticed at $P\lozenge.1_{rural}$ and $P\star.1_{rural}$ as a reduction in the SNR margin with respect to right-hand-side locations ($P\lozenge.2_{rural}$ and $P\star.2_{rural}$), under line-of-sight. The urban measurements show the influence of infrastructures on reliability. For instance, $P\circ.2_{urban}$ was measured with no surrounding buildings, whereas in $P\triangle.3_{urban}$ and P⬠$.2_{urban}$ buildings were present. Our experiments show that LoRaWAN presented no communication problems in rural scenarios, with low SFs being sufficient for wide areas. Conversely, the urban results call for high SF allocations, since only SF12 achieved 100% of success.

6. Conclusions

This work presents an Industry 4.0 solution for R-SCM based on a heterogeneous IoT network following DSC objectives. BLE and RFID technologies are proposed for inventory management using Smart Containers, while a LoRaWAN context network is responsible for environmental monitoring of industrial facilities. The network is governed by a Hybrid Gateway, responsible for receiving BLE information and forwarding it to two back-ends: an inventory-monitoring platform in AWS (via MQTT) and a context-information platform in TTN (via LoRaWAN). This solution was developed within a real IoT prototype and applied to an industrial case study regarding WEEE recovery towards CE.

Four performance tests were conducted to evaluate the proposal: *data ingest* (assessing the influence of increasing traffic), *geographical spread* (wide-area communication), *data size* (varying payloads) and *network latency* (end-to-end evaluation). Our results achieve reasonably appropriate network latencies for inventory management, suggesting that BLE communication might become a potential bottleneck for large-scale deployments. In such situations, the minimum receiving time at the Hybrid Gateway increases proportionally with the number of Smart Containers and, in addition, lower advertising intervals result in faster communications at the expense of lower effectiveness. Furthermore, a LoRaWAN-based coverage study was carried out in Albacete (Spain) concerning urban and rural scenarios. Our results show how dis-

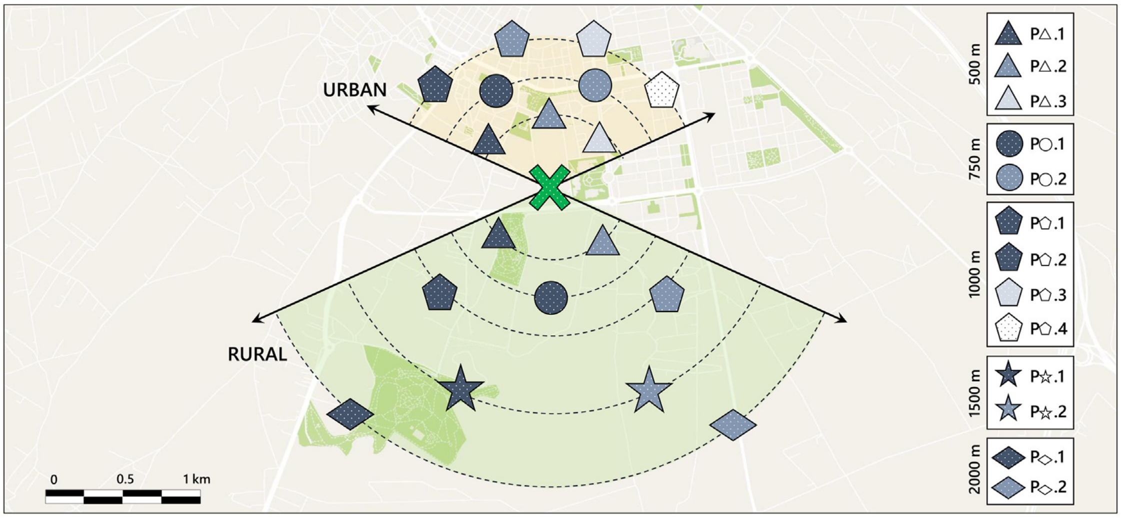


Fig. 8. Coverage study scenario in the city of Albacete with urban and rural locations.

Table 8
Geographic spread test results showing RSSI (dBm) and SNR (dB) metrics of LoRaWAN technology in urban and rural scenarios (range in meters), with a coding rate (CR) of 4/5, bandwidth (BW) of 125 kHz.

Reference	Range	SF7/DR5			SF8/DR4			SF9/DR3			SF10/DR2			SF11/DR1			SF12/DR0		
		RSSI	SNR	Q	RSSI	SNR	Q	RSSI	SNR	Q	RSSI	SNR	Q	RSSI	SNR	Q	RSSI	SNR	Q
P△.1$_{urban}$	534	-118	-2.2	✓	-117	0.2	✓	-119	0.0	✓	-119	-3.0	✓	-119	-5.2	✓	-118	1.0	✓
P△.2$_{urban}$	475	-114	2.8	✓	-114	2.5	✓	-119	-7.2	✗	-114	1.0	✓	-118	2.0	✓	-117	-0.5	✓
P△.3$_{urban}$	493	N.S.	N.S.	✗✗✗	N.S.	N.S.	✗✗✗	-120	-12.8	✗✗	-119	-10.8	✗	-120	-10.0	✓	-120	-13.8	✓
P○.1$_{urban}$	710	N.S.	N.S.	✗✗✗	-119	-8.0	✗	-118	-10.5	✗	-119	-6.5	✓	-121	-10.0	✓	-119	-6.2	✓
P○.2$_{urban}$	727	-119	-6.8	✗✗	-118	-10.8	✗✗	-120	-12.2	✗✗	-120	-9.0	✓	-120	-8.2	✓	-121	-12.2	✓
P⬠.1$_{urban}$	978	N.S.	N.S.	✗✗✗	N.S.	N.S.	✗✗✗	N.S.	N.S.	✗✗✗	-119	-16.2	✗✗✗	-120	-15.6	✗✗	-119	-17.2	✗
P⬠.2$_{urban}$	918	N.S.	N.S.	✗✗✗	N.S.	N.S.	✗✗✗	N.S.	N.S.	✗✗✗	N.S.	N.S.	✗✗✗	N.S.	N.S.	✗✗✗	-120	-17.5	✗✗
P⬠.3$_{urban}$	1031	N.S.	N.S.	✗✗✗	N.S.	N.S.	✗✗✗	N.S.	N.S.	✗✗✗	-121	-15.5	✗✗	-120	-14.8	✗	-121	-16.0	✗
P⬠.4$_{urban}$	988	N.S.	N.S.	✗✗✗	N.S.	N.S.	✗✗✗	N.S.	N.S.	✗✗✗	-121	-15.5	✗✗	-120	-16.0	✗✗	-119	-17.2	✗
P△.1$_{rural}$	514	-101	6.5	✓✓	-105	9.8	✓✓	-107	10.5	✓✓	-110	7.5	✓✓	-102	9.2	✓✓	-97	8.0	✓✓✓
P△.2$_{rural}$	491	-105	8.0	✓✓	-112	4.8	✓	-108	7.2	✓✓	-108	7.2	✓✓	-107	6.8	✓✓	-103	8.5	✓✓
P○.1$_{rural}$	757	-113	5.0	✓✓	-115	1.8	✓	-117	2.5	✓	-115	2.5	✓	-114	3.0	✓	-109	6.2	✓✓
P⬠.1$_{rural}$	1063	-114	3.0	✓	-113	4.8	✓	-111	5.2	✓✓	-111	3.8	✓	-111	5.0	✓✓	-114	5.0	✓✓
P⬠.2$_{rural}$	1036	-121	-7.0	✓	-118	-1.0	✓	-119	0.2	✓	-114	2.0	✓	-115	3.2	✓	-111	5.5	✓✓
P☆.1$_{rural}$	1439	-120	-7.0	✗✗	-119	-8.5	✗✗	-120	-5.2	✓	-118	-7.0	✓	-120	-3.2	✓	-119	-4.8	✓
P☆.2$_{rural}$	1556	-109	5.8	✓✓	-110	5.2	✓✓	-113	4.8	✓	-109	6.2	✓✓	-112	5.8	✓✓	-113	5.5	✓✓
P◇.1$_{rural}$	2037	-119	-6	✗✗	-118	-2.8	✗	-119	-4.8	✓	-118	-2.8	✓	-117	-3	✓	-110	-0.8	✓
P◇.2$_{rural}$	2107	-118	-3.0	✓	-118	-1.2	✓	-119	0.2	✓	-118	0.0	✓	-118	1.2	✓	-115	1.8	✓

tance as well as interposed buildings or vegetation areas impact on the perceived signal quality. Finally, we experimentally show to what extent higher SF allocations increase the coverage area and discuss its implications.

The deployment and evaluation of a network prototype serve as a demonstrator of the potential of IoT adoption in R-SCM scenarios, which carries important managerial insights. Stakeholders could benefit from this solution achieving better management of resources based on real-time inventory information through a low-cost and low-power infrastructure. Additionally, seamless monitoring of facilities is achieved through a self-monitored context information network able to report shop-floor incidences. With data-sharing being one of the barriers towards IT adoption, the proposed approach enables the use of data-encryption algorithms to control information accessibility depending on established relationships between manufacturers and R-SCM operators. As a result, IoT can be conceived as a tool to facilitate information management in EoL product-recovery operations contributing to the shift towards the CE.

As future work, we plan to assess the economic and environmental viability of the proposed approach for different types of products, considering factors such as their degree-of-deterioration, their added-value according to condition, or the required remanufacturing operations. Furthermore, based on the results obtained in this work, the IoT communications network proposed will be used as a testbed to develop algorithms oriented to test and improve the energy efficiency and reliability of communications, while improving the network capacity of LoRaWAN and BLE technologies in real industrial scenarios. For this, we aim to develop scheduling algorithms able to minimize collisions in the network and, thus, improve reliability through avoiding repeated transmissions.

Declarations of interest

None.

Acknowledgments

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