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A Real-Time Monitoring System of the Supply Chain Conditions, Products and Means of Transport

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***Abstract*—**Real-time monitoring of the supply chain conditions and procedures is a critical element for the optimal coordination and safety of the deliveries, as well as for the minimization of the delivery time and cost. Real time monitoring requires IoT data streams, which are related to the conditions of the products and the means of transport (e.g., location, temperature/humidity conditions, kinematic state, ambient light conditions, etc.). These streams are generated by battery-based IoT tracking devices, equipped with appropriate sensors, and are transmitted to a cloud-based back-end system. Proper handling and processing of the IoT data streams, using predictive and artificial intelligence algorithms, can provide significant and useful results, which can be exploited by the supply chain stakeholders in order to enhance their financial benefits, as well as the efficiency, security, transparency, coordination and sustainability of the supply chain procedures. The technology, the features and the characteristics of a complete, proprietary system, including hardware, firmware and software tools - developed in the context of a co-funded R&D program - are addressed and presented in this paper.

***Keywords*—**IoT embedded electronics, real-time monitoring, tracking device, sensor platform.

I. Introduction

One of the largest and emerging markets worldwide is related to the services and the automation of the supply chain, aiming at the safe, cost-effective and seamless transport of goods anywhere in the world. RETIMO which stands for 'Real Time Monitoring' is a research program/project [1] which started in 2019 and was proposed, managed and developed by the Greek company 'PEOPLE Private Company' (PPC). The program is co-funded by the ESPA Partnership for Growth Framework 2014-2020, titled 'Research-Create-Innovate'. The target of the RETIMO project is the design and development of a complete system, which comprises innovative IoT hardware, firmware and software tools, to support supply chain stakeholders throughout the transportation and handling procedures of goods, towards the optimal coordination and safety of their delivery, as well as the minimization of the delivery time and cost. Over the last five years, PEOPLE has focused its research efforts on the global supply chain market and is the patent holder of the lightest metal Shipping Container in the world (the 'Container 2.0'), which contributes to a considerable reduction of the transportation costs and the environmental footprint of the supply chain.

Managing the transportation of huge volumes of goods presents challenges which can be tackled effectively only with the adoption of modern IoT technologies, based on smart tracking devices and information systems (IS), able to manage and process huge volumes of data (procedures known as 'big data analysis'), in order to provide significant and exploitable results, within a required timeframe. In the context of the RETIMO project, PEOPLE aimed at developing an 'eco-system' of proprietary tracking devices and an IS, which would support the vision for enhanced efficiency, security, transparency, coordination and sustainability of the supply chain. Therefore, the system consists of:

- smart IoT tracking devices, which can be installed on different entities of the supply chain, like containers, trains, trucks and pallets,
- a back-end system, which carries out data processing, analysis and presentation, and offers interconnection with existing solutions, like automated Warehouse Management Systems (ERP, WMS) and electronic monitoring of cargo and transportation procedures (e-freight, e-documents, etc.),

and provides the following features:

- grouping of the supply chain entities (containers, trains, trucks, pallets),
- periodic transmission of IoT data streams, which source form the IoT tracking devices,
- real-time alarms and notifications, sourcing from the IoT tracking devices and the back-end system, respectively,
- use of blockchain technology, in order to enhance the transparency and 'accountability' of the collected IoT data streams,
- data analytics and decision support, based on the collected IoT data streams, using predictive algorithms and artificial intelligence (AI, machine learning).

The paper is organized as follows: Section II provides an overview of the structure of the system developed in the context of the RETIMO project. Section III describes the technical characteristics and functionality of the IoT tracking devices. In Section IV, the technology of the back-end system, as well as the methodology followed for its development, is addressed. Section V concludes the paper.

II. System Description

The back-end system collects IoT data streams from the IoT tracking devices through the cellular network, exploiting the LTE Cat M1 or GPRS radio access technologies (RAT) and embedded SIMs (eSIM). The IoT data steams include device location and status. Data are analyzed and processed by the back-end system and results are presented to the end user, via an appropriate frond-end application. The user can interact with the frond-end in order to view the status of all tracking devices, historic data and reports, as well as to remotely configure various parameters of the devices, like:

- Periodicity of transmissions.

- Activation/deactivation of individual alarms.
- Alarm levels/thresholds of all embedded sensors.

The structural parts of PEOPLE's 'eco-system' are depicted in Fig. 1 and are briefly described subsequently:

1) The back-end system: a cloud application software, able to communicate and interact with the IoT tracking devices.
2) The IoT tracking devices:
a) 'DoubleL': a battery-powered tracking device, which can be installed in containers or mounted on trains and trucks.
b) 'Flex': a battery-powered tracking device, which can be mounted on small trucks, vehicles, pallets and boxes.
c) 'Coin': a battery-powered temperature, humidity & light level data logger, which is installed on pallets and in product transport boxes.
3) The Mobile Application: an application for mobile phones with Android or IOS operating systems. It 'interacts' with the back-end system via the mobile's Internet connection and with the IoT tracking devices via the mobile's Bluetooth radio. The communication with the devices is encrypted and is used for remote firmware updates, configuration and data access.

III. RETIMO IoT Tracking Devices

The IoT tracking devices were designed following the lines of the '1220-2005 IEEE Standard for Application and Management of the Systems Engineering Process' [2] and comply with the provisions and the relevant EN standards of EU Directives and Regulations.

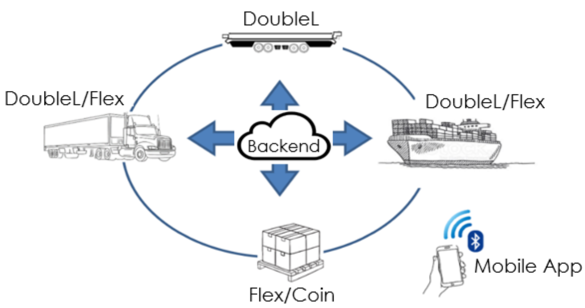

Fig. 1 IoT real-time monitoring system of the supply chain

Tests related to the RE Directive [3], the LV Directive [4], the EMC Directive [5], as well as various performance tests (EN 12830, IK, IP, vibration and shock) were carried out with device prototypes by labs certified with ISO 17025. Moreover, appropriate materials and production procedures were defined in order to ensure the compliance of the devices with the RoHS and WEEE Directives [6], [7]. The IoT tracking devices are depicted in Fig. 2.

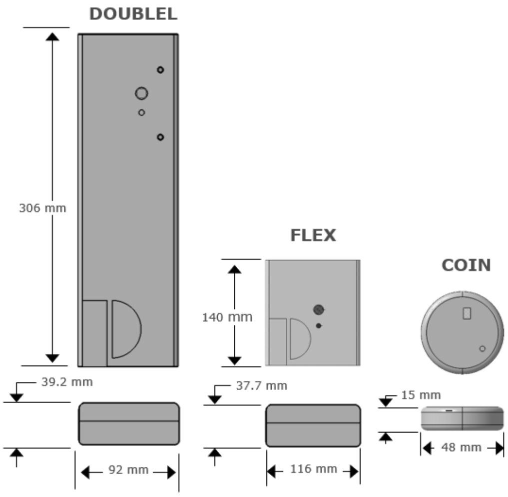

Fig. 2 IoT tracking devices

A. Device Functionality

1) DoubleL and Flex IoT Tracking Devices

These devices were designed to measure and report to the back-end system, via periodic transmissions over the cellular network, the following parameters:

- Location data (coordinates) and time (unix timestamp), via assisted GNSS.
- Location data via the cellular network.
- Number of satellites detected by the GNSS receiver
- Velocity in m/s.
- Ambient light level in Lux.
- Door status: open/closed (via light level and magnetic field detection).
- Temperature level with typical accuracy ± 0.1 ºC and resolution 0.01 ºC.
- Humidity level with typical accuracy ± 1.5% Relative Humidity (RH) and resolution 0.01% RH.
- Battery voltage and state of charge (SoC).
- Bluetooth MAC addresses of all neighboring devices (DoubleL, Flex, Coin).
- Message ID, hash key, BLE Network ID and configuration parameters (like the firmware version and the alarm thresholds).

Except from the periodic transmissions, the DoubleL and Flex IoT tracking devices will transmit various alarms to the back-end system, in real-time, whenever these alarms occur:

- Door open/close alarm.
- Motion start/stop alarm.
- Shock alarm.
- Tilt alarm.
- High/low temperature alarm.
- High/low humidity alarm.
- Low battery level alarm.
- Alarm of loss of Bluetooth connectivity with neighboring devices (DoubleL, Flex, Coin).

IoT data streams are transmitted from the DoubleL and Flex IoT tracking devices with the HTTPS protocol with TLS 1.2. Whenever a message is transmitted from a tracking device to the back-end, the back-end acknowledges (ack) data reception and provides to the device, along with the ack, various configuration parameters or information for a remote firmware update. During the next transaction, namely in the context of a scheduled/periodic transmission or an alarm, the back-end system will verify the correct application of the configuration parameters or the successful update of the firmware version of the device. If the tracking device does not receive an ack from the back-end or if data transmission fails for any reason (e.g., due to connectivity issues), the device will store the message and transmit it to the back-end along with the HTTPS message of the next transaction. This ensures data integrity and seamless data flow from the device to the back-end. The aforementioned mechanism is depicted in Fig. 3. Regarding the format of the message payload, this is a proprietary JSON structure which employs a blockchain mechanism, with the use of a hash key in every HTTPS message, enhancing security against rogue actions.

2) Coin IoT Tracking Devices

The Coin devices are wireless multi-sensors able to measure temperature, humidity and light level. They are not equipped with a cellular transceiver or a GNSS receiver, achieving in this manner low cost, small volume and weight (which makes them suitable for use even in very small boxes). The Coin devices transmit stored periodic measurements to the back-end, either via the Mobile Application (see Section II) or via neighboring DoubleL/Flex devices, sharing the same Bluetooth Network ID. Moreover, their firmware and configuration parameters (i.e., clock, measurement frequency, alarm thresholds) are remotely programmable from the Mobile Application or neighboring DoubleL/Flex devices.

B. IoT Tracking Device Hardware

The electronics of the DoubleL and Flex IoT tracking devices comprise high quality integrated circuits (ICs), passive components and battery, which were selected in order to support the SRS (System Specification Requirements) of the project.

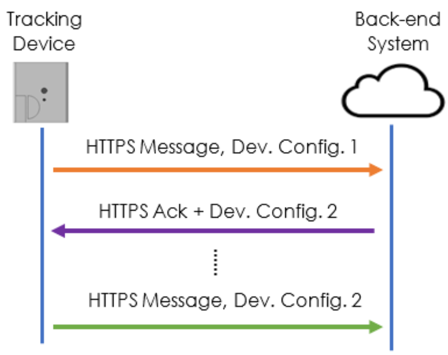

Fig. 3 Back-end and IoT tracking device transaction mechanism

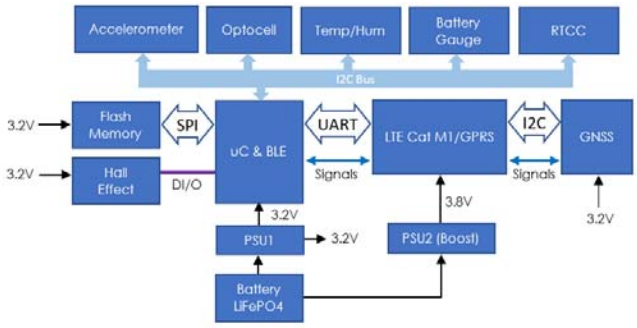

Fig. 4 Hardware architecture of the IoT tracking devices

The most important electronic components, along with information regarding their communication interface and manufacturer, are provided in Table I. Fig. 4 depicts the hardware architecture of the IoT tracking devices. It must be noted that the only difference between the DoubleL and Flex devices is the battery type: DoubleL is equipped with a rechargeable LiFePO4 prismatic battery, with capacity 25 Ah (3.2 V), while Flex carries a much smaller rechargeable LiFePO4 32700 cell, with capacity 6 Ah.

TABLE I
DOUBLEL/FLEX HARDWARE - MAIN ELECTRONIC COMPONENTS

Electronic Component	Comm. protocol	Mfn
Microcontroller & BLE	UART/I2C/SPI	Laird
Real Time Clock & Calendar	I2C	ST
GNSS Receiver	I2C	Ublox
LTE Cat M1/ GPRS Transceiver	UART/I2C	Ublox
Flash Memory	SPI	Winbond
Accelerometer & Gyro sensor	I2C	ST
Temperature & Humidity sensor	I2C	Sensirion
Battery Gauge sensor	I2C	Texas Inst.
Optocell sensor	I2C	Texas Inst.
Hall Effect sensor	Digital I/O	Texas Inst.

The hardware of the Coin devices is a subset of the electronics used for the DoubleL and Flex devices, including only a Microcontroller-BLE unit, a Real Time Clock & Calendar (RTCC), a temperature - humidity sensor and an optocell. The battery used for the Coin devices is a primary Li cell 2477, 1000 mAh (3.3 V).

The BoM (Bill of Materials) of the hardware was selected for high quality and credibility, wide operating temperature range (at least -20 ^oC to 60 ^oC) and low current consumption, which ensures long lifetime, reaching:

- up to 2 years for the DoubleL devices,
- up to 8 months for the Flex devices and
- up to 1 year for the Coin devices,

depending on the use profile (i.e., number of transmissions per hour) and the 'operational environment' (i.e., cellular and satellite connectivity).

IV. RETIMO BACK-END SYSTEM

As it is mentioned in the previous sections, the back-end system interacts with the IoT tracking devices: it collects, analyzes and processes IoT data streams sourcing from the devices, configures their parameters and updates their firmware.

The development of the back-end system was based on the following phases:

1) Analysis of system requirements. In this phase, the requirements of the system were analyzed – defined, based on intensive 'interaction' with potential customers and users of the system, mainly stakeholders of the supply chain 'industry'.
2) Definition of software technologies and tools. Based on the requirements defined in the first phase and comparing different existing solutions, the .NET Framework with C# and the SQL Server (RDBMS) were qualified as the most appropriate software tools for the development of the back-end system. Furthermore, the Identity Server 4, which implements the OpenID Connect (OIDC) standard, was selected for the authentication procedures.
3) Design and modeling. In this phase, tools like the UML (Unified Modeling Language) and Microsoft Visio were employed in order to 'visualize' and simply the software development phase.
4) Software development. In this phase, the software applications and the database of system were developed, using the tools and following the lines defined in the two previous phases.
5) Software testing. During this phase, various tests were performed in order to detect and eliminate possible bugs and evaluate the quality of the software and its compliance with the initial requirements. Software testing included the following discrete levels:
   a) Unit tests. Tests which checked the correct execution of routines/functions, using test data.
   b) Integration tests. These tests verified the successful collaboration between different software components.
   c) System tests. With these tests, the correct operation of specific use-cases was evaluated.
   d) Acceptance tests. They were performed with the assistance of potential users of the system (see also Section V), in order to verify that the system meets the needs of their business/organization. In the context of this test level, a considerable number of tracking devices was distributed to collaborating companies presenting intensive product transportation activity (pharmaceutical and food).
   e) Durability tests. The operation of the software was tested for 'worst-case' scenarios, namely in adverse conditions (e.g., unexpected shutdowns of the server), which is very important for the development of recovery plans.
   f) Scalability tests. The software was tested to evaluate its stable operation in case of increased numbers of users and IoT tracking devices.
6) System deployment and maintenance. Once the necessary tests had been performed, the product was launched on the Microsoft Azure Cloud platform and is maintained on a daily basis.

V. Conclusions

In this work, the technology, the features and the basic characteristics of a complete, proprietary real-time monitoring system, which aims at the supply chain 'industry' and comprises hardware, firmware and software tools, were presented. Extensive laboratory and field tests, as well as actual trials carried out by potential users, proved the suitability of the system for the supply chain market and product handing procedures.

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References

[1] ESPA Partnership for Growth Framework 2014-2020, Research-Create-Innovate, code T2EΔK-04894.
[2] IEEE 1220-2005 - Standard for Application and Management of the Systems Engineering Process.
[3] Directive 2014/53/EU of the European Parliament and of the Council of 16 April 2014 on the harmonisation of the laws of the Member States relating to the making available on the market of radio equipment and repealing Directive 1999/5/EC Text with EEA relevance.
[4] Directive 2014/35/EU of the European Parliament and of the Council of 26 February 2014 on the harmonisation of the laws of the Member States relating to the making available on the market of electrical equipment designed for use within certain voltage limits Text with EEA relevance.
[5] Directive 2014/30/EU of the European Parliament and of the Council of 26 February 2014 on the harmonisation of the laws of the Member States relating to electromagnetic compatibility (recast) Text with EEA relevance.
[6] Directive 2011/65/EU of the European Parliament and of the Council of 8 June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment Text with EEA relevance.
[7] Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE) Text with EEA relevance.