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Original
Investigation on wireless communication for sensors in IoT cold chain / Dilillo, Nicola; Ferrero, Renato; Gandino, Filippo; Rebaudengo, Maurizio. - ELETTRONICO. - (2023), pp. 89-93. (Intervento presentato al convegno AgriFood Electronics (CAFE), IEEE Conference on tenutosi a Torino, Italy nel 25-27 September 2023) [10.1109/CAFE58535.2023.10291686].

Publisher:
IEEE

Published
DOI:10.1109/CAFE58535.2023.10291686

Investigation on wireless communication for sensors in IoT cold chain

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***Abstract*—Thermal monitoring is a key requirement for cold chain management. In this context, the Internet of Things (IoT) offers new opportunities for dense and/or large-scale deployment of sensors, which need to collect data to effectively control the cooling system. Various technologies are used for data transmission. Although Bluetooth is widely exploited for transmitting data in IoT applications, its use in the cold chain management is rare. In this paper, the architecture of an IoT temperature monitoring system is studied and the technological choices of its components are analyzed and compared. In particular, the paper focuses on IoT node boards with Bluetooth, in order to highlight the opportunities of a currently undervalued technology. A theoretical analysis highlights its benefits for the application context and evaluates its suitability for monitoring systems suitable for cold rooms. The theoretical results are supported by an experimental analysis based on the implementation of different systems.**

***Index Terms*—cold chain, Internet of Things, RFID, Bluetooth, sensors, communications technology, computers and information processing**

I. INTRODUCTION

The cold chain refers to a temperature-controlled supply chain process for perishable items, such as fresh fruits and vegetables [1], dairy products [2], meat [3], seafood [4], vaccines [5], and certain pharmaceuticals [6]. By keeping appropriate temperature conditions, the cold chain ensures quality, freshness, and safety of items from the point of production or processing to the point of consumption [7]. The cold chain involves storage and handling of products in a temperature-controlled environment such as refrigerated warehouses or cold rooms; transportation with refrigerated vehicles such as trucks or containers; distribution and delivery at retail locations where the products are displayed in refrigerated sections to maintain their freshness until purchase by consumers [8].

Due to the strict temperature requirements, the cold chain adds complexity and stress to logistics operations, with subsequent increasing costs [9]. However, the emergence of Internet of Things (IoT) has helped streamline cold chain logistics to a certain extent, promoting it as a source for competitive advantage. Indeed, IoT sensors and devices can enhance efficiency and visibility throughout the supply chain, by offering real-time monitoring, traceability, remote control, comprehensive information exchange, and data analysis [10], [11]. Therefore IoT applications in logistics are widespread, including for example wine production [12], livestock farming [13], etc.

IoT is a broader term that includes both physical devices with some type of sensors, and the communication medium among information sources, computing resources, and humans [14]. In order to investigate the relevance of IoT for the cold chain, and to identify the main enabling technologies in this scenario, an extensive bibliometric analysis was performed. The results, discussed in Section II, point out interesting findings. In particular, the radiofrequency identification technology (RFID) is by far the most popular wireless communication mode [15], [16], relegating alternatives to sporadic uses. A such large adoption may be explained with the reliable performance of the RFID technology even with the harsh requirements in the cold chain, such as cold and humidity resistance, reduced battery consumption at low temperatures, etc. The current paper aims at evaluating whether Bluetooth can be a viable alternative to RFID for data acquisition and sharing. It should be noted that RFID is a broad concept, including many protocols. Basic classifications are based on the energy source of the RFID nodes and on the frequency used for trasmitting data. Active RFID nodes are equipped with a battery, while passive RFID nodes are powered by the electromagnetic energy transmitted from an RFID reader. This distinction is relevant for the frequencies reserved internationally for industrial, scientific, and medical (ISM) RFID-based applications. Passive RFID nodes can operate at 125 KHz and 134 KHz (low frequency), 13.56 MHz (high frequency) and from 860 to 956 MHz (ultrahigh frequency). Active nodes use 433 MHz or 2.45 GHz. Section III describes the implementation of an RFID system and a Bluetooth system for monitoring the temperature and humidity in a refrigerator. In particular, an active RFID sensor operating at 433 MHz is considered. The performances of the two systems are compared in Section IV and finally the conclusions are given in Section V.

II. BIBLIOMETRIC ANALYSIS AND RELATED WORK

An extensive bibliometric analysis was conducted based on data retrieved from two scientific databases: Scopus and Web of Science. In the query formulated on Scopus, the string “cold chain” was searched in the article title, abstract and keywords. Only English articles were considered, without any

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This publication is part of the project NODES, which has received funding from the MUR—M4C2 1.5 of PNRR with the grant agreement no. ECS00000036.

TABLE I: Occurrences of terms among the keywords of papers related to cold chain.

Family	Term	Scopus		Web of Science	
		author keyword	index keyword	author keyword	Keyword Plus
Communications technology	Internet of Things (IoT)	87	141	42	1
	wireless sensor networks (wsn)	34	47	17	10
	cloud computing	6	14	4	0
	Internet	4	27	3	9
	routing	5	10	1	0
	Zigbee	5	9	4	1
	Bluetooth	5	6	4	1
	smart contracts	5	2	3	0
Computers and information processing	Internet of Things (IoT)	87	141	42	1
	blockchain	38	70	23	1
	digital storage	0	88	0	0
	real time systems	7	42	7	0
	computer viruses	0	40	0	5
	big data	9	30	4	4
	Internet	4	27	3	9
	cloud computing	6	14	4	0
	industry 4.0	8	4	1	0
Sensors	radiofrequency identification (RFID)	66	96	44	7
	temperature sensor	10	33	10	7
	thermometer	0	22	0	0

constraint on the publication time. On June 1st 2023, the query returned 4,614 documents; the results were exported as plain text including citation information, author keywords, and index keywords. Author keywords are freely chosen by the authors, whereas indexed keywords are standardized terms chosen by Scopus in order to take into account synonyms, various spellings, and plurals. Among the 4,614 documents, 3,440 of them have author keywords and 3,608 have index keywords. Overall, 17,661 unique author keywords and 90,297 unique index keywords were found.

A similar search was executed on Web of Science. Due to singular/plural sensitiveness, the strings “cold chain” or “cold chains” were searched in the topic field, which corresponds to title, abstract, author keywords, and Keywords Plus. Keywords Plus are terms automatically generated from the titles of the documents. Two bibliographic sources were included in the search: Science Citation Index Expanded (SCI-EXPANDED), and Conference Proceedings Citation Index - Science (CPCI-S). On June 1st 2023 the query returned 3,272 results. Among them, 2,549 documents were provided with author keywords and 2,511 with KeyWords Plus. Overall, 10,224 unique author keywords and 8826 unique Keywords Plus were found.

The keywords of the retrieved documents were analyzed according to the IEEE taxonomy [17]. This taxonomy comprises 51 term families (or branches), i.e., the main IEEE topics. For each term family, the document provides a three-level hierarchy of detailed terms. A term can appear in more than one hierarchical branch. In the current context, three term families appear of particular relevance: “communications technology”, “computers and information processing”, and “sensors”. The bibliometric analysis counted how many times each detailed term appears among the keywords of the papers retrieved from Scopus and Web of Science. In particular, the counting for each term included narrower terms and alternate forms, as specified in the IEEE thesaurus [18]. The thesaurus is a vocabulary of almost 11,500 engineering, technical and scientific terms. It provides a semantic relationship of each term with broader terms (BT), narrower terms (NT), alternate forms (UF), and related terms (RT). For example, UF of the term “radiofrequency identification” are “RFID”, “radio frequency identification”, and “radio-frequency identification”, whereas NT is “RFID tags”.

Table I lists the terms appearing at least 20 times among the index keywords, which are the largest group, or at least 5 times among one of the other kinds of keyword. Not surprisingly, “Internet of Things” is the most popular term, as it can be viewed as a broad umbrella of enabling technologies for the cold chain. It is noteworthy that the only keyword with a similar occurrence is “radiofrequency identification”: this is by far the most adopted technology for traceability, authentication, and process automation in the cold chain. Other relevant concepts are:

- “wireless sensor networks” for monitoring parameters such as temperature, humidity, light, motion. Temperature is the essential measure, as indicated by the keywords “temperature sensor” and “thermometer”.
- “cloud computing”, which provides storage, processing power, and data analytics capabilities in order to manage large-scale deployments and handle data-intensive applications. Some of these features are captured also by other keywords, such as “digital storage”and “big data”.
- “blockchain” and “smart contracts” for enhancing the security, privacy, and trustworthiness of the cold chain.

Besides the RFID technology, the analysis on keywords reveals that other connectivity protocols are seldom used in the cold chain scenario. In particular, there are only 11 distinct papers where Bluetooth appears as keyword, and in a couple of cases it is considered as an alternative to Zigbee [19], [20]. It is mainly adopted to transmit data from sensors to a gateway. For example, in the management of tuna, which requires a

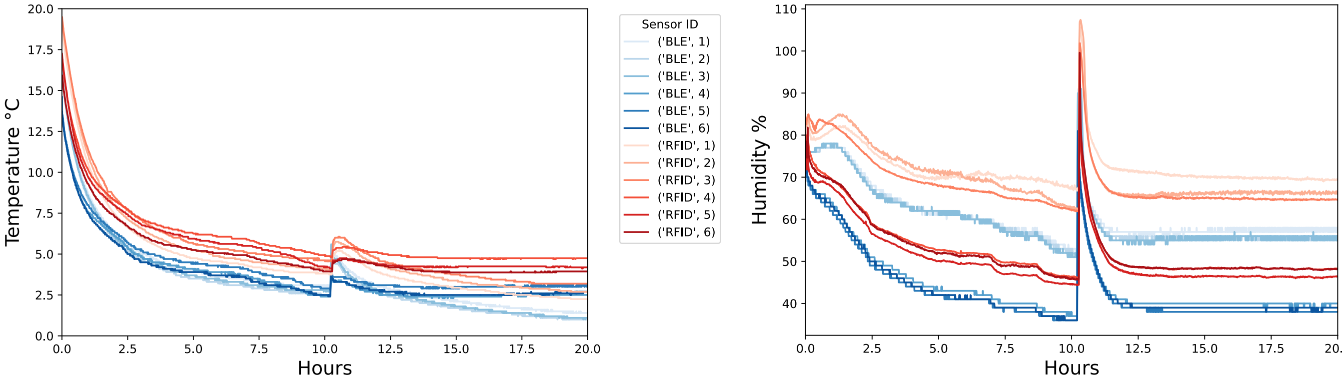


Fig. 1: Temperature and humidity measured

temperature of -60°, cold rooms are equipped with Bluetooth transmission systems, and form a mobile self-organization master/slave network. The data is then forwarded to 5G gateways [21]. Other similar applications regard the transport of foods in insulated containers without refrigeration [22], a high-level cold chain management framework [23], and a social network for monitoring the cold chain [24]. Here, data is collected using Arduino boards and transmitted with Bluetooth modules to a gateway. In other works useful devices for the cold chain are equipped with a Bluetooth transmitter, such as an insulating shipping container [25], and an amperometric sensor of ascorbic acid, which is helpful for quality control of fresh products [26]. Other applications proposed in literature concern the development of an antenna for Bluetooth sensors that performs at low temperatures [27], and a human tracking system based on Bluetooth signals, with the aim of ensuring the safety of workers [28], [29].

III. METHODOLOGY

A use case has been settled in order to compare RFID and BLE technologies. The ELA PUCK RHT, an active RFID sensor that works in operating mode at 433.92 MHz, has been selected as representative RFID system. It is specifically designed for periodic measurement of temperature, in a range from -40° to 80°, and humidity, in a range from 0% and 80%. This device is autonomous, robust and compact, boasting a waterproof feature, with a rating of IP68. It can be easily programmed to adhere to the specifications:

- ID, to recognize the sensor;
- time interval, between consecutive transmission.

In the experiments the time interval between transmission was set to 8.1 s, because the temperature inside the refrigerator does not change rapidly. Two frames are sent at the end of each interval: the first one with the temperature value and the second one with the humidity. Each frame contains information about:

- sensor ID;
- type of measure (temperature or humidity);
- measured value .

According to the datasheet [30], the ELA WIFI RFID reader can retrieve and process the frames transmitted by the ELA PUCK RHT device up to a distance of 100 meters in open field. It reads the RFID frames and communicates the information, through a socket interface, to a receiving server.

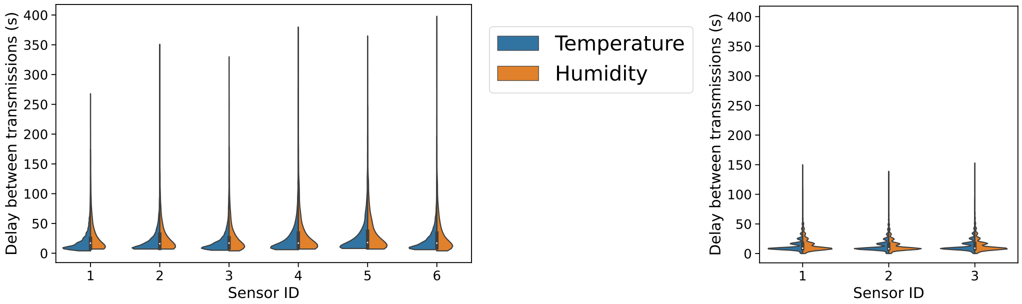
An STM32l152 Nucleo board, a low-cost prototyping system from STMicroelectronics, has been utilized in the BLE systems. The board was equipped with the SPBTLE-RF module, to enable BLE communications, and the DHT11 sensor, to measure temperature and humidity. The Nucleo hardware and software ecosystem provides an easy way to develop and evaluate embedded system applications. In this setup, one board has been designated as the server, while multiple boards function as clients, depending on the desired number of sensors. During operation, the server establishes connections with each client individually, utilizing polling techniques, to retrieve the corresponding measured values of temperature and humidity, which are sent together, along with the associated client ID. Subsequently, the server board communicates this information, through a serial interface, to a receiving server.

In both the RFID and BLE systems, a server application stores the transmitted data along with its timestamp.

To evaluate the effectiveness of RFID and BLE sensors in a cold chain setting, two experiments were conducted. In the first one, in order to assess the cold chain conditions, temperature and humidity values were measured by placing 6 RFID and BLE sensors inside a refrigerator, for a duration of 20 hours. Beko RDSA240K20W is the consumer fridge used in the tests, with a capacity of 177 litres. Its annual energy consumption is 226 kWh/year and the storage time at power outages is 16 hours. The refrigerator was initially set to have the highest temperature and, before starting with the measurements, it was adjusted to the lowest temperature. In the middle of the experiment, the refrigerator was intentionally opened to induce a rapid temperature change. In the second experiment has been used only 3 sensors, to evaluate the scalability of both systems.

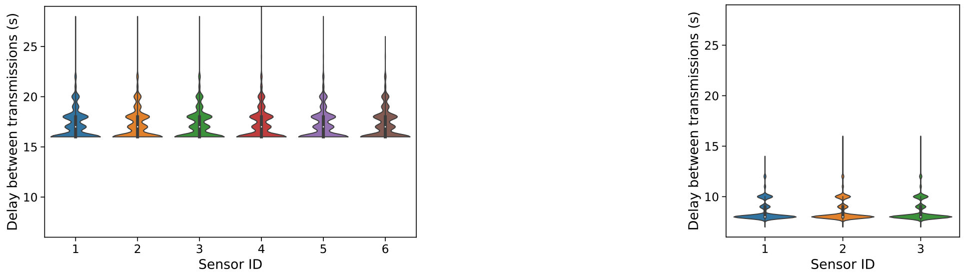
IV. RESULTS

Values of humidity and temperature measured during the first experiment are depicted in Fig.1. They exhibit a similar trend in the RFID and BLE systems: the only noticeable difference is a slight shift that can be easily compensated.



(a) Experiment 1 (b) Experiment 2

Fig. 2: Distribution of delay between two consecutive successful transmissions of the same measured value (temperature or humidity) in the two experiments with the RFID system. Note: temperature and humidity are sent separately.



(a) Experiment 1 (b) Experiment 2

Fig. 3: Distribution of delay between two consecutive transmissions in the two experiments with the BLE system. Note: temperature and humidity are sent together in a single transmission.

This offset can be observed in the RFID sensors and may be attributed to its robust and compatct packaging, which leads to a slight increase in the device temperature and consequently affects the measurements, shifting a bit the value.

In the RFID systems, frames are transmitted every 8.1 s. However, due to collisions among them and interference with the environment, the reader samples them at varying time intervals. As the number of sensors grows, the probability of collisions also increases. Consequently, the average time between two consecutive successful transmissions of the same data (temperature or humidity) increases with the number of RFID sensors, as shown in Fig. 2. In experiment 1, the average transmission time is approximately 16 s, with a maximum value of about 400 s; in experiment 2, the average transmission time is 11 s, with a maximum value of about 150 s.

The issue of collisions does not arise in the BLE systems, as the server directly queries the target client until it receives the expected response, resulting in a smaller variance in time distribution, almost equal to zero. However, similar to the RFID systems, the average time between two consecutive transmissions will increase with the number of BLE sensors utilized, as shown in Fig.3. In experiment 1, despite the average transmission time between two consecutive measurements remaining around 16 s, the maximum value obtained is now around 30 s, which is an order of magnitude lower than the RFID case. Instead, in experiment 2, the average transmission time is reduced to 7 s, enhancing the performance of RFID sensors, with a maximum value of approximately 16 s.

Despite the more predictable nature of BLE systems, there is still some variability in the delay between two consecutive transmissions. This is attributed to the time needed to send data from the board to the receiving server, which is not deterministic and depends on the latency of the communication channel. The same delay exists in RFID systems as well.

V. CONCLUSION

An extensive bibliometric analysis has revealed that RFID is by far the most adopted technology for data communication in the cold chain. Other technologies, such as Bluetooth, have been poorly exploited so far. In the current paper, some experiments have been carried out to compare the performance of an active RFID sensor, namely the ELA PUCK RHT, and a Nucleo board with a Bluetooth expansion module. The results reveal that both of them perform effectively, even if they exhibit distinct behaviours. In particular, the Bluetooth system demonstrated a more reliable performance compared to the RFID system, with higher configurability. Therefore, the current research emphasizes the use of Bluetooth as an effective alternative of RFID in the cold chain. This suggestion seems confirmed by recent market strategies: for example, the producer of the ELA PUCK RHT is migrating most of its products to the Bluetooth standard [31].

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