Using Battery-Less RFID Tags with Augmented Capabilities in the Internet of Things

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***Abstract*— Driven by user demand for new smart systems in the framework of the Internet of Things (IoT) and fueled by technological advances in Radiofrequency Identification (RFID), an increasing number of new IoT-oriented RFID-based devices has appeared in recent years in scientific literature. Some of them conjugate canonical RFID identification with extra functionalities such as sensing, reasoning, memorization, and actuation. In this way, IoT challenging applications can be developed, which distribute processing load till to the extreme nodes of the network, while lying upon the well-established RFID infrastructure. In this work, a reasoned panoramic on the potentialities in the IoT framework of augmented RFID tags is presented and classified. Two applicative scenarios are envisioned, presented and discussed, to illustrate how augmented RFID devices may support advanced IoT systems.**

***Index Terms*— Internet of Things, Sensors, Actuators, Power Management, RFID augmented Tags, UHF, Antennas.**

I. INTRODUCTION

RFID systems are recognized as one of the building blocks of the Internet of Things (IoT) because of their capability of easily and inexpensively support object/person identification. Indeed, the working principle of an RFID system is simple and effective. A device called "reader" continuously transmits a modulated RF signal, known as Continuous Wave (CW), through dedicated antennas. A second passive device, called "tag" and composed of an antenna and a chip with processing and storage capabilities, detects this signal, energizes its internal circuitry, interacts with the reader, retrieves the identification number stored into its data memory and sends it back to the reader.

Cost-saving and effective identification strategy are combined with other advantages, substantially consisting in a well-established infrastructure, universally-agreed protocols (e.g.; the UHF band Gen2 standard) and reliable middleware tools.

Such advantages are currently underexploited, as RFID role is usually confined to the mere identification task: RFIDs are commonly used to identify objects and to get basic static information about them. Further information being collected during object lifetime is usually archived into remote databases and accessed on the basis of the identification code. Other tasks, such as sensing, processing and actuation, are carried out by specialized devices and/or by remote services. This approach works fine for a number of applications which are nowadays well-established in the IoT arena, such as tracking physical objects within well-defined boundaries (e.g.; warehouses), but has severe power limitations for challenging IoT scenarios [1], [2].

Indeed, when sophisticated capabilities, such as reasoning on object data and object-to-object interaction, are required, decoupling the identification task from other ones may render the overall system cumbersome and inflexible. New appealing perspectives may open, instead, if things are converted into smart objects [3], able to sense their local situation, reason and interact with each other, possibly by concentrating all functions in a single device.

Therefore, one solution to join RFID advantages with IoT requirements consists in the design of RFID tags with augmented capabilities such as storage, computation, sensing, and/or actuation. In this way, when the tag is attached to the object, a compact smart device is obtained, whose interaction with the rest of the world is sustained by the RFID infrastructure.

A number of battery-less devices supporting novel RFID augmented systems are emerging in literature [4]-[12]. All devices are different from each other in terms of design, electromagnetic characteristics, sensitivity, working range, etc. Each tag is optimized for different purposes on the basis of specific IoT applications. Table I summarizes and compares the peculiarities of each tag in order to support the selection of the most suitable one on the basis of the sèecific application.

In particular, one of the first examples of augmented UHF RFID Tag is the wireless identification and sensing platform (WISP) that implements ID-modulation for sensor data transmission [5], [6]. A low-cost, general-purpose alternative to WISP is the sensor-tag (S-Tag) [11]-[13]. Based on a multi-ID approach, the S-Tag can be connected to generic sensors and, when interrogated by a standard EPC Class-1 Generation-2 (Gen2 for short hereafter) reader, it is capable of transmitting a proper combination of EPC codes that univocally encode the sensor value. A passive multi-standard RFID tag, enhanced with sensing and localization functionalities and implemented in a 0.13μ bulk CMOS process, has been presented in [7]. In [4], a well-performing device, called RAMSES (RFID Augmented Module for Smart Environmental Sensing), has been presented. RAMSES is a long-range, Gen2-compliant, and programmable augmented

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tag optimized for RFID-sensing and equipped with temperature, light, and acceleration sensors. When interrogated by a Gen2 reader, even from 10 m distance, RAMSES transmits back an ID code along with all the measured parameters.

In addition to the research activity, RFID manufacturers and suppliers have recently broken into the market with Gen2 tags that incorporate sensing, computing, and data-logging capabilities for unconventional RFID applications. Among them, the most interesting are the SL900A sensory tag by IDS Microchip [8], the Easy2Log tag by CAEN RFID [9], and the SensTAG by Phase IV [10].

Many of the named solutions [4], [7]-[13] are, however, basically meant only for RFID-sensing. Nonetheless, many applications could take good advantage, for instance, of a computation being distributed among diverse passive augmented tags or, again, from an information exchange among such tags. The device called SPARTACUS (Self-Powered Augmented RFID Tag for Autonomous Computing and Ubiquitous Sensing) [14], that is the augmented-tag realized by the same authors, embeds storage, computation, sensing, actuation, and communication capabilities, thus transforming physical objects into autonomous smart systems, whose interaction is supported by the RFID well-established infrastructure.

Without loss of generality, this last device will be used in this paper to offer a reasoned panoramic on the potentialities of augmented RFID tags in the IoT systems concretization.
IoT applications are, for simplicity, grouped into two sets: applications mainly relying on storage and processing capabilities (Section II) and applications focussing on interaction and/or actuation (Section III). The exemplificative implementation of novel IoT systems and related use cases is presented in Section IV. Finally, Section V draws some conclusions.

II. Object Data Storage And Processing

A large number of IoT applications are based on storage and access to object data. They include both traditional RFID ones, such as product traceability, and esoteric ones, such as “object life logging”. Indeed, recording object data may be useful in many situations. For instance, it may provide a valuable “memory support” to people having memory diseases or may help consumers being informed about the history of specific products, such as food, furniture, cars, etc..
In general, the IoT vision assigns to each object a personal profile, built upon data collected during object lifetime. Such data may be static (e.g.; object characteristics, needs and preferences) or dynamic (e.g.; experiences and interactions occurring during object lifetime). Moreover, data stakeholders may be pre-defined at design time (in the so-called *closed-loop* scenarios) or may be unpredictable (in the so-called *open-loop* scenarios). The former scenarios include traditional RFID applications, such as supply chain traceability. The latter ones include more flexible and challenging IoT applications, such as customer review recording, where data may be inputted at any time by different subjects, in an unpredictable way.
Closed-loop applications are often implemented by adopting the traditional RFID architecture, i.e.; the tag is mainly used to link the physical object to its virtual counterpart, and every object capability is delegated to a remote infrastructure. As memory is physically separated from the object, this solution is suitable for “*passive*” memory applications, i.e.; applications whose principal concern is memory update and access. In other terms, the object has no direct knowledge of itself and of its environment and cannot take initiatives on the basis of data stored in the memory banks associated to it.

In order to exploit RFID advantages (cost-effectiveness, universally-agreed identification strategy, relying upon the RFID well-established infrastructure) in the framework of an IoT architecture (where locality of processing and memory

TABLE I.
COMPARISON BETWEEN AUGMENTED UHF RFID TAGS

Reference	Read range (m) in fully passive	On-board sensors	Balanced Uplink and Downlink (same sensitivity)	Distributed Reasoning	Capability of managing actuators	Shared Memory	Private Memory	Use of FRAM	Gen2 compliance
SPARTACUS [14]	3.5	2 (temperature, light)	yes	yes	yes	yes	yes	yes	yes
RAMSES [4]	10	3 (temperature, light, acceleration)	no	no	no	yes	no	no	yes
WISP [5, 6]	4	2 (temperature, acceleration)	yes	yes	yes	yes	yes	yes	no
Multistandard tag [7]	8	1 (temperature)	yes	no	no	no	no	no	yes
SL900A [8]	1.5	1 (temperature)	no	no	yes	yes	yes	no	yes
Easy2Log [9]	Not provided	1 (temperature)	yes	no	no	yes	no	no	yes
SensTag [10]	4.5	1 (specified by the user)	no	no	no	yes	no	no	yes
Sensor Tag [11]-[13]	4	no	no	no	no	no	no	no	yes

capabilities, together with a more generic object self-consistency are envisioned) the memory embedded in RFID tags may be exploited: object data may time by time be stored into the tag attached to the object. This renders the solution more flexible and open to more challenging applications.

However, this solution exhibits several limitations when implemented with canonical RFID tags and also with some of the currently available augmented RFID devices. The main one is referred to the limit in the number of write operations. Therefore, when the object lifetime is long, there is no guarantee that the logging activity may go on during the whole object life. *T*his limit is exceeded, for instance, by some augmented tags like SPARTACUS and WISP, as they are equipped with FRAM, which can be written 10^{10} more times than EEPROMs, equipped on most RFID chips.

Moreover, in order to optimize memory exploitation, data logging should preferably be accompanied by adequate filtering and reasoning activities. This requires augmenting the tag with some computing capability, which is not provided by most available RFID devices.

The above constraints confine once again the RFID adoption to passive or short term memory solutions [15], [16]. However, some of the augmented tags available in literature, exceed such limits by embedding both an FRAM, and an ultra-low power microcontroller, providing adequate computing capability.

These features, joined with other augmented capabilities, allow for designing challenging data-driven IoT applications, where:

- *Private data stay with the object* – some novel devices have both a private and a public memory bank. Therefore, critical data which should be known only to the object (such as private experiences in case of human personal logger) may be stored on the private memory bank. When joined with a computation capability, this feature allows data to be accessed and elaborated locally when needed and, eventually, rendered accessible by making a copy into the public memory bank. In other terms, the object has the capability of deciding which information is private and when.
- *Data logging may include environmental information* - environmental data may be obtained 1) by sensors attached to the tag and 2) by interacting with the reader which may gather data from other sources of information, dispersed in the environment. Moreover, thanks to the reasoning capability of some augmented tags, each tagged object may select which environmental information is worth to be stored on the tag, on the basis of its personal preferences. Such information may also be filtered, aggregated and integrated at the local level. This capability may be useful in applications where gathering and processing data about context is critical, such as health monitoring and food traceability.

- *Data logging may include activity information*- Data logging may also be enriched with information concerning object activities. This is useful, for example, in applications which monitor human activity in specific diseases such as Alzheimer. Thanks to the capability of new tags emerging in IoT which support tag-to-tag communication (see next section), both machine-to-machine communication and human-to-machine interaction are supported. Therefore, each object is, in any moment, conscious of which objects are in the surrounding and how they relate with each other. An adequate processing of such information, together with a suitable format for codifying activity information, may then produce a sort of "portable diary" of personal interactions.

III. Interaction and Actuation

A large number of challenging IoT novel applications, such as object-based social networking, serious gaming, domotics and smart cities, are centered around interaction and responsiveness to the current context. On the basis of the input coming from the environment, these applications see objects taking decisions, triggering alarms, or requesting further information. In other terms, they strongly depend on object smartness , reactivity and communication capabilities.

However, the implementations of these kinds of applications [17], [18] mostly distribute object capabilities among specialized devices and software frameworks, each having a specific well-defined role (sensing, identification, storage, actuation, etc.) and rely on the Net to join them. In other words, the physical object is linked to diverse digital/physical counterparts being dispersed in the environment. As a result, a complex pathway has to be followed each time an object has to react to an external event and the connection between the concrete object and the action may damp down, this limiting system potentialities.

This can be avoided if the capabilities are physically attached to the object which owns them and a suited infrastructure is provided to sustain interaction between objects.

In agreement with this vision, novel augmented tags join storage, processing, sensing, communication and actuation capabilities into one compact transponder, which, when attached to physical objects, enables them to sense the environment and reason consequently. More in detail, it provides:

- *Re-activity and pro-activity* – Thanks to its processing capability, the tag may host software agents with pro-acting and re-acting capabilities. In other terms, the object possesses an autonomous capability of taking decisions.

- *Sensing and perception* – The tag may be attached to one or more sensors. Moreover, thanks to its processing capability, sensed data may be locally filtered, aggregated and analyzed. Therefore, data are cleaned at source level. This reduces network traffic and speeds up the object decision process.

Moreover, it is worth recalling that traditional RFID systems do not provide the certainty that, when a communication exchange begins, readers may access data loaded in memory by tags both in write and in read mode, as the write-mode can be shorter. To solve this problem, newest IoT-oriented tags guarantee that, every time the tag is visible to the reader, both kinds of operation can take place (pro-active two-way communication). This allows, for example, readers both to send commands to tags by writing special strings onto their memory and access processing results. Moreover, readers are networked with one another. Therefore, they can share data acquired during their interaction with other objects and software services. In other terms, readers may play both the role of 1) context data collectors and providers (Fig. 1) and of 2) bridges between remote objects thus enabling their interaction (Fig. 2). They both facilitate the interaction between objects and gather and deliver information about remote and/or past context data to objects being in their visibility range. The following example shows how the equality between write and read sensitivity improves tag2tag interaction as well.

Let us consider a network of readers (Fig. 2), each having a number of tags in its own visibility range. Suppose, then, that tagA needs to send a specific request to tagB (such as "please, compute the average temperature over the last two hours"). Then, tagA may send the request to reader1, which may, on its turn, broadcast it to connected readers. Reader2, then, may issue the compute request to tagB, which is in its visibility range. Such request consists in a "write" operation: reader2 writes a special "operation code" onto tagB memory. TagB interprets such operation code and writes the operation result onto its memory. Reader2 performs a "read" operation to access the result and send it to reader1, which finally communicates the value to tagA.

This kind of communication exchange allows tags (or readers) to take initiative, signaling events and request specific computations to other tags. It is performed by joining Gen 2 protocol and the capability of providing the same write and read sensitivity.

In conclusion, an augmented tag supports:

- *Interaction* - Diverse objects, being dispersed in the environment, can exchange data and information by interacting with the readers, which play the role of bridge to the rest of the world, i.e., to other tagged entities, databases, data sources dispersed in the environment and connected to the Net;

- *Clear separation between local and remote contextual information* - local information may be stored into object memory, whist remote data are obtained by interrogating the reader;
- *Distributed reasoning* – Complex applications, relying on the integration between contributions coming from distributed entities and systems, may be designed and implemented.

Finally, let us devote some considerations on *actuation* and *alert generation*. Traditional RFID tags do not support it. Therefore, when notification is needed, it is issued by readers. As a result, the system does not directly see the alert source. It knows the area where the alarm took place (the area covered by the reader issuing the notification) and the object ID. However, in some applications (such as object-based social networking and navigation), it is useful to physically identify the source of the notification. As different objects may co-exist in the coverage area of the reader, this can be a major limitation. With augmented tags, instead, notifications are directly issued by concrete objects. This reduces network burden and allows the system to promptly identify the source of the notification. Therefore, the following feature is supported:

- *Actuation and alert generation* – Thanks to embedded actuators, notifications are tightly linked to their issuers

IV. VALIDATION SYSTEM AND APPLICATION SCENARIOS

In this Section, it will be shown how augmented tag capabilities may be exploited for implementing complex IoT systems by describing two as simple as significant application scenarios. The former is in the sport area, the latter concerns object searching. For the sake of clearness, it is worth pointing out that, without loss of generality, the peculiarities of our proposed solution, SPARTACUS, are taken into account in the presented scenarios. Of course, it does not mean that some other augmented tags could not be used as well.

V.a Cross-country skiing race

RFID systems are widely adopted in the sport sector. They are mainly used for implementing timing [19] or athlete tracking [20] systems. However, current applications mostly assign to

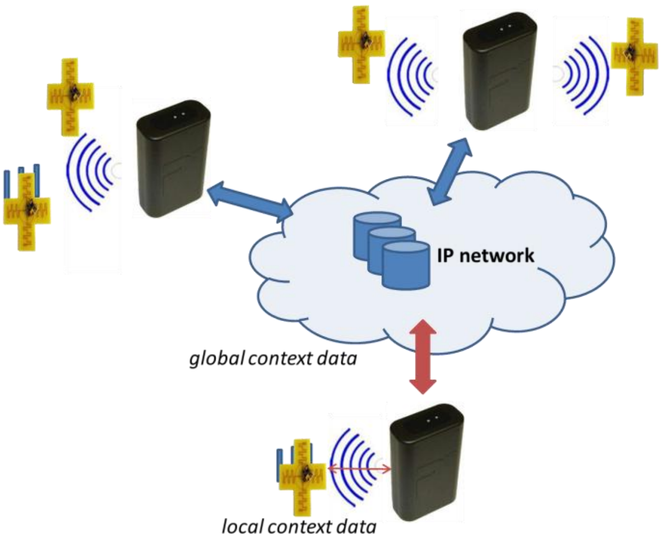

Fig. 1. Augmented tag to reader communication guarentees integration between local and global context data.

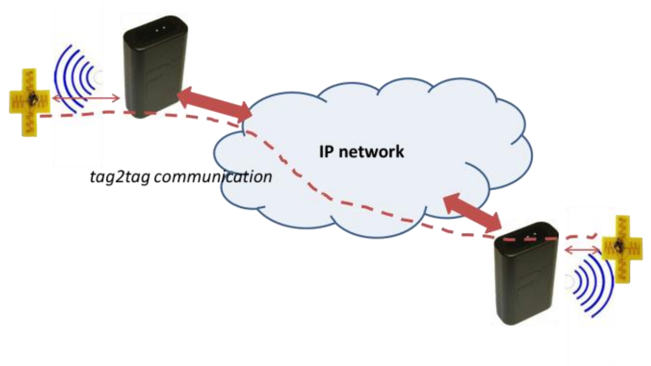

Fig. 2. Tag to tag communication mediated by readers interconnected via an IP network.

the RFID tag the task of identifying the athlete, whilst more complex tasks, such as data archive and processing, are delegated to the remote infrastructure. On the contrary, RFID tags with augmented capabilities assign an active role to the RFID tag, during and after the race. Indeed, during the race the tag accumulates and processes data, notifies events and interacts with the reader and the athlete. During and after the race, tag data can be accessed and integrated with other information. In this way, the tag becomes a sort of smart repository, which supports the player during the competition with timely information and provides a pleasant "souvenir" to be flipped through later.

For example, let us consider a cross-country skiing race and to equip skiers with an augmented RFID transponder. At each gate a reader is installed. Readers are connected via Internet.

Before the race begins, each tag is loaded with static data (such as total number of participants, number of gates, distance between gates, etc.).

During the race, athletes monitor race evolution by interrogating the tag. They can be informed about their position with respect to other athletes, the evolution of their performance, etc. This is feasible, because, each time the athlete enters in the visibility range of a reader, the following events occur:

1. The reader sends contextual data to the tag, such as the current timestamp, the number of athletes having already crossed the finish line, the number of athletes having crossed other gates, etc.
2. Based on both data stored in the tag and on data received by the reader, the tag calculates updated info concerning the athlete, such as: the time spent while going from the previous gate to the current one, the average speed, the estimated time to arrival, the estimated distance from the nearest athlete.

On the basis of data stored in its memory, the augmented tag can also trigger alerts viewable, for instance, by LEDs of different colors while passing the gates during the race. Moreover, the tag may also be interfaced with sensors monitoring the athlete's physical healthiness, thus alerting in case of excessive stress.

This proposed application scenario shows how novel augmented tags facilities provide to end-users:

- Data provision at end-user request – thanks to the actuation/sensing capability, end-users can request specific data, which can be locally visualized;

- Local processing - this feature speeds the output process, as data are available at local nodes (i.e.; the athlete tags);

- Added value services – the integration with sensors, for instance, can widen the range of application of this simple application;

Fig. 3 shows an example of interaction between the system devices operating in this application case.

The figure depicts two readers and a tag. The athlete owning the tag is supposed to be crossing Gate 1, which is in the visibility range of Reader 1. Reader 2 is supposed to be located at the next gate, i.e.; Gate 2. Both readers access a remote archive where they update data concerning athletes. Each time an athlete crosses a gate, the associated reader stores in the remote archive current data concerning the athlete, such as crossing time. In this way, the way race evolves is known to all readers.

More in detail, when an athlete crosses a gate, a bidirectional communication between the reader and the tag occurs, during which:

- The reader identifies the tag;
- The reader updates the archive with tag data (e.g.; current time and tag ID);
- The tag asks for contextual information (such as the time when the nearest competitor crossed Gate 2);
- Reader 1 gets contextual information from the Network and sends it to the tag;
- The tag computes data useful for the athlete (such as the acceleration needed to reach the nearest competitor)
- The tag visualizes alert on the basis of computed data by controlling LEDs of different colors while passing a gate.

Regarding the physical system implementation, some considerations related to the reading time and the elaboration latency of augmented RFID tags should be addressed for the cross-country skiing race case. If, for instance, SPARTACUS is used, a storage capacitor of 10 μF (see [14] for details) is sufficient to perform all the above mentioned operations. Moreover, a system setup composed of two-meter large gates with commercial RFID reader antennas installed on both sides and suitably oriented along the horizontal plane can be considered. In this operating conditions, if the maximum speed of the skier is of about 9 m/s (typical in similar cases) and about 500 ms are necessary to perform the computation at 1 m from the reader antenna, a proper RFID gate guaranteeing a coverage area of at least 4.5 m along the race direction must be considered. For instance, for each side, two 5-dBi-gain reader antennas placed at a height of 1.5 m above the ground and 2 m distant from each other can be adopted. For instance, a setup similar to that presented in [21] - [24] has been arranged to test SPARTACUS in these operational conditions.

V.b Object search and location

Several RFID systems have been proposed to provide information about object location. This is useful in many situations, such as searching for critical everyday objects, e.g.; keys or glasses, or locating defective products in a large manufacturing company.

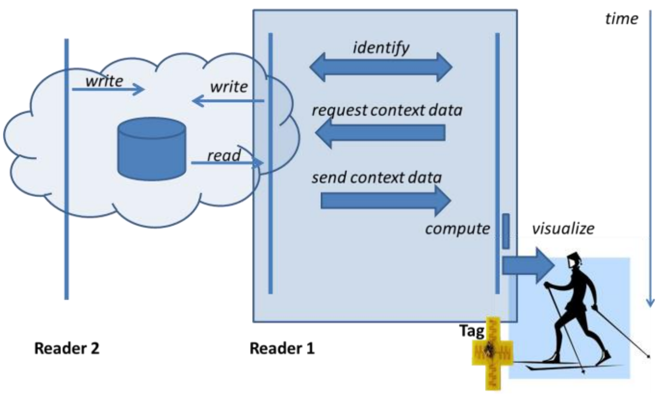

Fig. 3. An example of reader-tag interaction in the framework of the skiing race application scenario.

Grids of RFID tags [25], for example, have been designed to communicate spatial coordinates and information about the surroundings to visually impaired people equipped with mobile readers. However, in these systems, RFID tags are programmed upon installation. Therefore, the information provided to end-users is static. Moreover, its granularity depends on the grid resolution.

More challenging applications deal with the location of objects which change their position in an unpredictable way, such as manufactured products or personal belongings. In this case, tags must be attached to the single objects. However, current systems do not give any information about the precise location of the object, as the notification is issued by the reader. This happens because traditional tags are adopted, which separate actuation from its source.

In [26], for example, a system for assisting visually impaired people in a dynamic environment is proposed. A database maps object IDs to audio files containing the voice playback of the object name. When the reader comes into close proximity to the tag and energizes it, the tag returns the object ID, the reader interrogates the database and plays the corresponding audio file. In this way, the end-user acquires just the information that the object is in the nearby.

By adopting augmented tags a more precise and effective object location system can be provided, as single objects are equipped with autonomous identification, communication and actuation capabilities. A complete system for object searching may be built as follows.

Static data about objects, such as name and characteristics, may be loaded on tags by using a laptop computer attached to the reader. Such data may be enriched during object lifetime by end-users, which may be interested in "tagging" the objects by inserting easy-to-remember phrases. Then, when somebody looks for a specific object, a "look-up" string must be inputted to the reader (by using voice commands, in case of visually-impaired people). If the object is in visibility range of the queried reader, the object itself issues a notification, which may be visual or auditory, depending on the kind of application. Otherwise, other connected readers are queried and the system may inform the user about the current and/or the past position of the same object.

Fig. 4 shows a simple example of interaction between system devices operating in this scenario. The figure shows what happens when somebody inputs a search string to query a specific reader:

- The reader broadcasts the query;
- Each tag in the reader visibility range processes the query to verify the mapping between the inputted string and stored data;
- Only the matching tag issues the alert.

This simple application shows how augmented tags facilities can provide:

- Decentralization of the search process – Differently from other systems [27], search activity is carried out locally by tags. This renders the application framework flexible and lean;
- End-user control on object information – the user loads data on the object which may form a sort of "personal memory aid" which helps him/her in recalling object history;
- Exact location of the searched object – This is guaranteed by the actuation capability owned by tagged objects.

Fig. 5 shows the sequence diagram of the client application functionalities for the «object search» and the related data acquisition steps of the augmented tag. In particular, the end user enters the search keyword. The client application tells the reader to 1) filter SPARTACUS tags (by creating and implementing a ROSpec) 2) write the search string on tag's memory (by creating and implementing an AccessSpec) and 3) request SPARTACUS tags to perform the local search (by creating and implementing an AccessSpec). Tags matching the search string switch on their alarm and write a «success» string on their memory. This string is read by the client application and notified to the end-user.

The physical implementation of a system performing the smart object searching based on augmented RFID tags is relatively simple. Indeed, once each object is labeled whit an augmented tag, standard PDA readers are suitable to perform the object searching. Despite its simplicity, the system performance in terms of reading time and responsiveness are high. For instance, it has been verified that, when SPARTACUS is used to label the objects and a Nordic ID

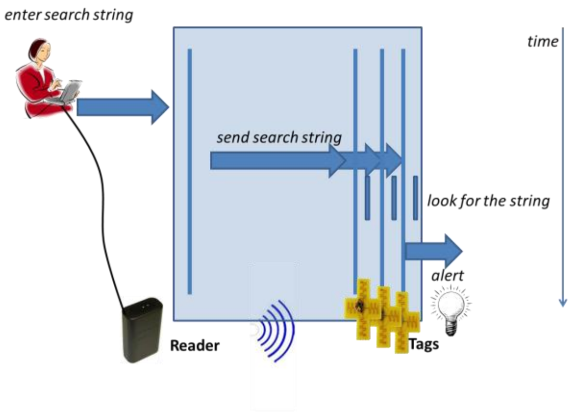

Fig. 4. An example of reader-tag interaction in the framework of the object search use case.

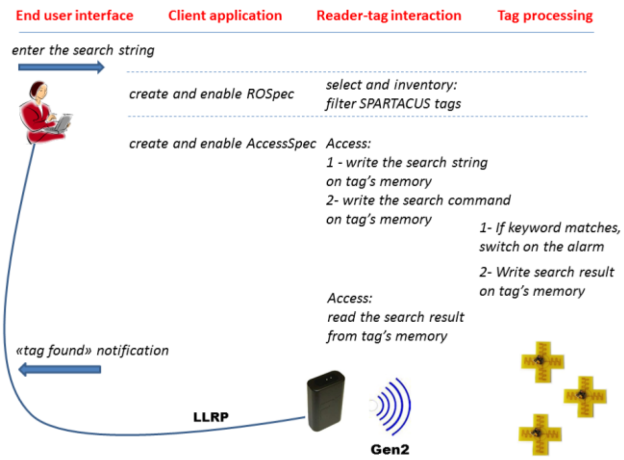

Fig. 5. Sequence diagram describing the data acquisition/management process for the use case of Fig. 6.

Cross Dipole reader [28] is used for searching, an average response time of about 2s is obtained within an operating range of 1m. In this time SPARTACUS correctly performs the above mentioned operations and locates a certain object by implementing the searching algorithm. Also in this case a storage capacitor of 10 μF has been considered.

V. Conclusions

In the last few years, thanks to accurate hardware design and optimization, different “augmented” passive RFID tags suitable to support smartness have been presented in literature. They aggregate in single passive devices storage and processing capability, communication, sensing, actuation, pro-active two-way reader-tag communication, and reliable long-term memory. In this paper, the potentialities of such new RFID tags in the IoT framework have been studied. Two applicative scenarios have been envisioned, presented and discussed, to illustrate how augmented RFID devices may support advanced IoT systems.

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