it-RFID: an Ultra-Low Power Active RFID system with flexible Radio Triggered Wake-Up System

A. Sanchez*, Y. Boo†, S. Blanc*, and J.J. Serrano*

* ITACA - Universitat Politècnica de València. 46022 València, Spain
† Beijing University of Posts and Telecommunications (Internship in ITACA)

Abstract—Radio Frequency IDentification (RFID) systems are becoming a very interesting solution for several applications. Although “passive” RFID systems are widely used because no energy source is needed on the tags, emergent “active” RFID technology (with an on-board battery) opens the door for new applications with challenging requirements. However, energy must be saved in “active” tags to extend its lifetime. Although RFID standards (ISO/IEC 18000-7) define some mechanisms to reduce power consumption using some wake up signal prior to any data exchange, state-of-the-art platforms do not implement this feature and waste lots of power. In this paper a new active it-RFID platform is presented that complies with ISO standard and reduces energy consumed drastically by embedding a new wake up system that combines the advantages of the highest performance systems. it-RFID performance is evaluated and compared with other solutions as well as other solutions based on Wireless Sensor Networks (802.15.4).

Keywords: RFID, Active RFID, WSN, RT-WUp

1. Introduction and Related Work

Radio Frequency IDentification (RFID) is an automatic identification method using radio frequencies between RFID readers and tags. A reader or interrogator is the device in charge of collecting the tags’ information within its RF communication range. A tag is a small transponder that contains certain information collected by the reader for different purposes.

Traditionally, the most widely approach to RFID systems is “passive” RFID technology, in which a “tag” has no power source of its own [1]. Recently, “active” RFID (with an on-board battery in the tag) has become an interesting alternative [2].

Passive tags suffers from extremely short communication range. Both the transmitter and the receiver performance of the in-built transponder are very low. Using a battery, active Radio Frequency (RF) transponders can be used with highest output power and more sensible receivers, thus range is extended. Besides sensors, memory and other elements can be embedded in a tag to flexibly obtain, process, store and transmit information. As a result, active RFID advantages enables a wide range of new applications. Nevertheless, active RFID tag lifetime is limited since energy available is finite. Specifically, wireless link consumes most of the power [3].

Several works have been done on obtaining a RFID protocols with ultra-low power consumption [3], [2]. However in most RFID real deployments, devices from various vendors can be used and they must be able to work together. For this reason, compatibility and interoperability between systems that comply with an international standard is advisable. ISO/IEC 18000 [4] is a series of standards that define the air interface for RFID devices. Although there are several parts, part 7 is the standard for active RFID systems. Although ISO/IEC 18000-7 has been proved to be inefficient [5], this paper is not focused on improving this specification, but designing a new active RFID platform that increases the active RFID application performance, and still complies with ISO 18000-7 standard.

The most remarkable research papers on active RFID platforms are based on micro-controller architectures with some configurable radio interface [5] [6] [7]. However, all these platforms have the same problem: tags are not able to efficiently detect the presence of a reader and to save power when not actually needed. For that purpose standard ISO/IEC 18000-7 contemplates the emission of a wake up signal previous to any data exchange. This signal should activate or wake up (WUp) all the tags within RF reader range. However, available platforms do not implement this feature and tags remain active listening to the channel for long time waiting for reader detection, wasting lots of power.

This wake up issue is tackled by Radio-Triggered Wake Up (RT-WUp) techniques. Using this feature, a wireless system can be activated asynchronously by a specific radio signal and turned into operative mode. State-of-the-art wake up systems [8] [9] are able to activate remote nodes within a range of 15 meters dissipating less than 9 µW when waiting for incoming wake up signals. Both systems are based in super-heterodyne receivers: incoming Radio Frequency (RF) signal is moved to a much lower Intermediate Frequency (IF). The resulting wave can be further processed and decoded with lower power consumption.

In this paper a new active RFID platform is described.
It combines a micro-controller based architecture with the best performance wake up system [9]. This system has been enhanced to extend detection range and to fulfil ISO/IEC 18000-7 specifications: a new flexible IF receiver has been investigated that combines flexible IF wake up architecture [8] with the selected wake up system [9].

The rest of the paper is organized as follows. Standard ISO/IEC 18000-7 is described in Section 2. In Section 3 the new it-RFID platform is described. Section 4 shows performance of this new platform showing the results obtained from different experiments. Finally, Section 5 concludes the paper.

2. Active RFID protocol ISO/IEC 18000-7

The tag collection algorithm defined in ISO/IEC 18000-7 uses a medium access protocol based on the framed slotted ALOHA protocol. Fig. 1 shows the tag collection sequence and timing as defined in ISO/IEC 18000-7 [4].

Reader initiates the communications in a Reader Talks First (RTF) fashion, as described in [2]. First, sends a wake up signal that is able to activate (wake up) all the tags within the RF communication range. The standard describes this wake-up signal as a sub-carrier tone of 30 kHz. Immediately afterwards, the reader sends a collection command and then all tags’ data are collected by repeating a number of collection rounds. Some authors label both wake up signal and collection command together as Beacon [2].

The windows size is specified in the collection command and it defines the total time for the reader to listen for potential responses from tags. This value is defined as a multiple of 57.3 ms. Initial window size is set to 57.3 ms and then it is dynamically resized depending on collisions detected on the tag responses.

On the other side, upon receipt of a collection command, tags calculate the slot size (8 ms) and the number of slots in the current collection round using the specified window size and randomly select a slot in which to respond.

2.1 Power consumption issues and it-RFID motivation

After the window has elapsed, the reader sends point-to-point sleep commands to all tags collected during the collection round. The tags that receive a sleep command move to sleep mode and do not participate in the subsequent collection rounds. Sleep mode is an ultra-low-power state in which the whole tag consumes a few micro-watts. The tags can remain in sleep mode until next wake up signal is detected.

However, as discussed in Section 1, currently there is no active RFID platform that is able to detect wake up with real low-power consumption. Tags listen to the channel periodically instead and, upon Beacon detection, tags respond and wait for sleep command to start checking periodically the channel again [2]. This channel checking task dissipates lots of power as evaluated in Section 4.

Therefore it would be desirable to avoid this periodic checking. Moreover, energy will also be saved with an
active RFID platform that a tag to allows a tag to remain in sleep mode when no RFID is available.

3. it-RFID platform

Fig. 2 shows the it-RFID overall architecture. As previously discussed, the main advantage of the solution presented in this paper is the attachment of a RT-WUp system that tackles both transmission and reception of ISO/IEC 18000-7 wake up signals with ultra low power consumption.

On the one hand, RFID reader is only formed by a transponder with reconfigurable radio interface to comply ISO 18000-7. Additionally it incorporates a wired interface to a remote station, but it is out of scope of this paper. On the other hand, RFID tag is composed by the same transponder and a wake up receiver circuit [9]. As explained in [9], reader radio interface is reused to transmit both RFID data and the wake up signal. This fact favours system integration and decreases final system costs [10]. The details of the different parts are explained below.

3.1 Radio Frequency Interface

The presented platform in this work has been based on the radio interface developed by the company Wireless Sensor Networks Valencia (WSNVAL) [11]. Its microcontroller core is CC1110 (Sub-1GHz System-on-Chip with 8051 MCU) from Texas Instruments (TI). It includes CC110X radio interface and can operate in 433 MHz, 868 MHz and 900 MHz bands.

Although this system was originally developed for Wireless Sensor Networks (WSN) deployment, radio parameters such as centre frequency (433.92 MHz), symbol frequency deviation (50 kHz), data-rate (27.7 kbps) and modulation (FSK) can be reconfigured by changing internal registers to fulfill ISO/IEC 18000-7 specifications.

Radio Interface power consumption transmission (TX), reception (RX) and sleep mode represents to whole it-RFID platform power consumption when running these tasks. These energy values are shown in Table 2.

3.2 Radio Triggered Wake-Up system

Radio Triggered Wake Up (RT-WUp) is an asynchronous wake up technique that keeps WSN nodes in a ultra-low power mode until a certain radio signal is detected. Wake up signal, emission and reception are critical and are accurately described and solved in [9].

3.2.1 WUp Signal

Wake up reception needs a specific wake up receiver sub-system that remains active most of the time listening to the channel. Since active RFID tags energy resources are limited, the hardware should dissipate as low power as possible to detect, decode and process high frequency wireless wake up signals. As discussed in [9], On-Off-Keying (OOK) saves much power.

Attending to the WUp receiver features, a wake up signal can be either a simple tone or a 8 to 16 bit pattern, which is compliant with 30 kHz sub-carrier defined by ISO/IEC 18000-7 standard. An example of OOK wake up signal is shown in Fig. 3.

3.2.2 WUp Transmitter

The RFID reader does not need any additional hardware apart from the in built transponder. The reader needs additional firmware to transmit suitable WUp signals as depicted in Fig. 3. WUp tones are generated by the reader micro-controller by setting an auto-reload timer at double the desired modulation frequency (60 kHz in ISO 18000-7 case) and by changing RF output power (from maximum to zero and vice-versa) upon timer overflow. Output RF carrier signal suffers On-Off switch generating a square wave of the desired frequency On-Off-Keyed.

Power dissipated to generate and emit this signal is equal to the power consumed when emitting FSK data packets.
3.2.3 Configurable IF Super-heterodyne WUp Receiver

WUp receiver block diagram is shown in Fig. 4. This subsystem is based in a super-heterodyne structure in which an incoming signal is shifted to a lower Intermediate Frequency (IF) to be further processed. This technique has been proved to improve receivers performance [9] [8]. After filtering RF signal to avoid potential interferences, the resulting signal is mixed to a lower frequency band. Then this IF signal is processed by a commercial wake-up detector which can set a flag to activate the micro-controller.

The original wake up solution presented in [9], operates using a fixed intermediate frequency: 125 kHz. This value was set by the decoder: AS3930 [12]. As discussed by the authors, this block is critical to achieve optimal solutions for both wake up signal detection range and power consumption, reporting indeed the lowest consumption (8.7 µW) and the greatest range (15 m) until now.

An interesting alternative to both improve wake up signal detection with a potential frequency deviation is reported in [8]. Using a flexible and uncertain intermediate frequency, radio-frequency blocks are simplified and the overall behaviour improves significantly. This concept is shown in Fig. 5. IF varies within a certain range. Therefore, the decoder must be able to decode wake-up signals with this uncertainty. Using this technique authors improved significantly its previous wake up receiver [13] sensitivity (50 %) and reduced its power consumption (20 %).

it-RFID wake up receiver implements “flexible frequency range concept” to the WUp system presented in [9]. Modern low frequency wake up signal decoders have improved their performance. e.g. AS3933 [14]. This chip is compatible with the previous decoder AS3930 and implements some new interesting features. Decoded signals can not only be fixed to 125 kHz, but take a certain value from 15 kHz to 150 kHz as shown in Fig. 5. Besides, this decoder includes an internal 3 dB low noise amplifier that can be activated on demand. Decoder sensitivity increases from 100 to 80 µV rms (20 %) and only extra 300 nW are dissipated.

Using the design methodology explained in [9] to embed a low-frequency decoder into a high frequency system, a new radio-triggered wake up receiver has been obtained. Since both WUp signal and transmitter can upgraded with this new enhancement by changing the WUp transmitter firmware, the result is a new radio wake up system with flexible IF.

Finally, this new wake up system has been successfully attached to the it-RFID architecture and final performance is evaluated in Section 4.

4. it-RFID evaluation

To carry out a full evaluation, a prototype of the whole proposed it-RFID platform has been developed. ISO/IEC 18000-7 message collection protocol has been implemented according to the specifications explained in Section 2.

In this paper two features are evaluated: the new flexible IF WUp system improvement compared to original WUp solution [9]; on the other hand an evaluation in a realistic scenario of the power consumption of it-RFID compared with Free2move active RFID solution [5] and with a 802.15.4 WSN platform (CC2430 from TI) [2].

4.1 Detection Distance

Maximum distance reported using the original wake up receiver was 15 meters [9] and power dissipated was 8.7 µW. In this section the proposed improvements of the new WUp system are evaluated as well as their convenience attending to the impact on other features such as power consumption, costs, etc.

Firstly, the decoder in-built 3dB amplifier performance. When active, receiver sensitivity improves and is reflected in a wake up detection range increase from 15 to 17.5 meters (16 % improvement). Since power
consumption only raises 11\% while distance raises 16\%, it is advisable to use this feature in most of the cases.

Secondly, the new flexible IF feature has been also evaluated. The decoder is capable of detecting WUp signals within 15 and 150 kHz, divided in 5 frequency ranges: 15-23, 23-40, 40-65, 65-95, 95-150 kHz. WUp signal detection range is measured for each of these sub-bands.

Results are shown in Table 1. Different bands are evaluated using the following frequencies: 20 kHz, 30 kHz, 50 kHz, 80 kHz, 125 kHz. Since additional 3dB amplifier is active to obtain the best performance results, two improvement values are calculated:

- **Partial improvement** that compares the range measured with the it-RFID wake-up with 3dB gain boost activated;
- **Overall improvement** that compares the results with the original WUp system.

As can be seen in Table 1, the lowest intermediate frequency, the widest range measured. OOK demodulator block in wake up receiver (Figure 4) is based in a Dickson Charge pump composed of diodes and capacitors [9]. It has been observed that even capacitors with a few Farads are not completely charged and discharged with highest IF values. Using lower IF, OOK demodulator efficiency increases, decoder input voltage raises and range is consequently extended.

### 4.2 Power Consumption

Although lots of work has been done to improve ISO/IEC 18000-7 standard -specially power consumption- this work is not aware of improving the protocol itself, but evaluating the power consumption of it-RFID platform compared to other active RFID platforms used as reference.

To evaluate it-RFID power consumption, an scenario similar to the proposed in [2] has been set. Originally, authors compared Free2move (F2m) active RFID platform [5] implementing a Reader Talk First (RTF) protocol ISO 18000-7 compliant, with a standard WSN 802.15.4 platform based on CC2430 from TI (15.4). it-RFID with presented wake up enhancement ISO/IEC 18000-7 compliant is added to this comparative in Table 2.

RFID readers have not been considered since they are usually powered by the mains and their power consumption is not critical. However, active RFID tags energy buffers are usually limited and it is really interesting to evaluate their consumption in order to estimate their operation lifetime.

Power consumption values of all three platforms when running different tasks related to active RFID protocol -as proposed in [2]- are reported in Table 2. Since it-RFID and Free2move platforms implement RTF version of ISO 18000-7, different tasks duration are the same in both cases.

The main advantage of it-RFID is the exploitation of the RT-WUp to perform ISO 18000-7 WUp signal or even the whole Beacon detection. Only if the wake up signal is detected, tag switches to receive (RX) mode to decode the incoming collection command, remaining in sleep mode otherwise. Other platforms needs to periodically check the channel. This value is compared in $\hat{E}_{\text{Beacon}}$ row of Table 2.

The improvement has been evaluated in a real case scenario with some simple assumptions to avoid effects related to upper layer issues such as medium access, application, etc. Let’s consider an application with one single tag and one single reader. Under this assumption we can assume that if a tag is near enough to detect reader Beacons (20 meters), tag responses are collision free and no extra collection rounds are needed in one collection round. Thus, two situations are possible: a reader is available or not.

On the one hand if a reader is available, the collection sequence explained in Section 2 is carried out. The energy consumed by a tag in one cycle can be calculated using (1). As shown in Fig. 1 two messages are sent from the reader (Collection and Sleep Command), and one is sent back from the tag (Tag Response). The rest of the time the node is sleeping.

$$E_{\text{reader}} = \hat{E}_{\text{Beacon}} + E_{\text{TX}} + E_{\text{RX}} + E_{\text{Sleep1}}$$  \hspace{1cm} (1)

Using expression (1), it is estimated a consumption per cycle of 0.466 mJ for the Free2move platform, 0.78 mJ for the 802.15.4 platform and 0.55 mJ for the it-RFID platform. When reader is available, it-RFID is a balanced solution among the three compared platforms due to the radio chip power consumption.

On the other hand if a reader is not available, the energy calculated per cycle can be estimated using (2). While energy consumed by 802.15.4 solution is 1.25 mJ, Free2move consumes 0.47 mJ and it-RFID only consumes 9 $\mu$J, which is three orders of magnitude below the other platforms.

$$E_{\text{no reader}} = \hat{E}_{\text{Beacon}} + E_{\text{Sleep2}}$$  \hspace{1cm} (2)

Attending to the previous results, it can be concluded that power savings depend on the presence of a reader.

<table>
<thead>
<tr>
<th>Frequency (kHz)</th>
<th>Range (m)</th>
<th>Partial Improvement (%)</th>
<th>Overall Improvement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>20</td>
<td>14.3</td>
<td>33.4</td>
</tr>
<tr>
<td>30</td>
<td>20</td>
<td>14.3</td>
<td>33.4</td>
</tr>
<tr>
<td>50</td>
<td>20</td>
<td>14.3</td>
<td>33.3</td>
</tr>
<tr>
<td>80</td>
<td>17.5</td>
<td>0</td>
<td>16.7</td>
</tr>
<tr>
<td>125</td>
<td>17.5</td>
<td>0</td>
<td>16.7</td>
</tr>
</tbody>
</table>
Table 2: Terms, power, duration time, and energy consumed by: Free2move (F2m), 802.15.4 (15.4) and it-RFID (it)

<table>
<thead>
<tr>
<th>term</th>
<th>Power [mW]</th>
<th>duration [ms]</th>
<th>( \frac{E_{cycle}}{15.4} ) [mJ]</th>
<th>explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_{Beacon} )</td>
<td>57</td>
<td>0.009</td>
<td>2.5</td>
<td>avg. energy consumption when trying to receive a beacon signal, no reader available</td>
</tr>
<tr>
<td>( E_{RX} )</td>
<td>57</td>
<td>0.003</td>
<td>3.1</td>
<td>avg. energy consumption when transmitting one payload packet to a reader</td>
</tr>
<tr>
<td>( E_{TX} )</td>
<td>42</td>
<td>0.003</td>
<td>3.4</td>
<td>energy consumption when sleeping after successfully delivered payload to a reader</td>
</tr>
<tr>
<td>( E_{Sleep1} )</td>
<td>57</td>
<td>0.003</td>
<td>3.5</td>
<td>energy consumption when sleeping after listening for a beacon, no reader available</td>
</tr>
<tr>
<td>( E_{Sleep2} )</td>
<td>57</td>
<td>0.003</td>
<td>3.5</td>
<td>energy consumption when sleeping after listening for a beacon, no reader available</td>
</tr>
</tbody>
</table>

To get a wider perspective, different scenarios have been considered simulating the presence and the absence of readers with a certain probability. For each scenario, energy consumed during 24 hours operation is calculated for both platforms.

Results are shown in Fig. 6. 802.15.4 based tag consumes less power when a reader is present. Although it seems a contradiction, to check the channel waiting for Beacons dissipates actually more power than emitting and receiving packets. In Free2move platform, energy consumption remains almost constant since it consumes approximately the same energy either with a reader present or not. Finally, it-RFID draws the minimum power when a reader is absent while power consumption increases as long as radio is used to transmit useful information when a reader is present (it-RFID Energy Consumed in Fig. 6), what is much closer to the optimal case.

it-RFID improvement is also evaluated in Fig 6. it-RFID Energy Normalized curve represents the Free2move and 802.15.4 energy to it-RFID energy ratio (expressed in %) for each scenario. More than 98 % energy can be saved if there is no reader available. Nevertheless, up to 11 % can be wasted in scenarios with a reader available all the time compared to Free2move, but still saves 29 % compared to 802.15.4 solution.

Finally, another interesting energy analysis proposed in [2] is the estimation of a small CR2032 lithium cell lifetime (3V/180mAh). Authors selected the case in which no reader was available. In this paper we extend these results with it-RFID performance and also considering the case in which a reader is available all the time. These results are shown in Table 3.

Since power consumption of it-RFID with reader absent (9 \( \mu \)W) is even lower than the power consumption of Free2move platform in sleep mode (11 \( \mu \)W), battery lifetime using it-RFID is even longer than Free2move ideal case (Free2move considering that no extra power is needed to detect a Beacon). If a reader is available, differences decrease and all the solutions deplete the battery energy before two months.

Table 3: Battery lifetime when no available reader is present and reader is present all the time

<table>
<thead>
<tr>
<th>Platform</th>
<th>3V/180mAh CR2032 lifetime [days]</th>
</tr>
</thead>
<tbody>
<tr>
<td>No reader</td>
<td>Reader</td>
</tr>
<tr>
<td>Free2move</td>
<td>48</td>
</tr>
<tr>
<td>802.15.4</td>
<td>18</td>
</tr>
<tr>
<td>it-RFID</td>
<td>2586</td>
</tr>
<tr>
<td>Free2move ideal</td>
<td>2045</td>
</tr>
</tbody>
</table>

5. Conclusions and Future Work

In this paper it-RFID is presented. A new active RFID platform ISO 18000-7 standard compliant has been developed and tested using a prototype. The platform is enhanced with a Radio Triggered Wake Up system to improve RFID Beacons detection, reducing RFID tag power consumption while no RFID readers are present.

A new Radio Triggered Wake Up system has also been designed. It is based on a super-heterodyne Wake Up Receiver with flexible Intermediate Frequency and additional 3dB low power amplification. We have observed an improvement of 33 % distance compared with the original wake up system. This new system has been successfully attached to it-RFID.

it-RFID performance is compared with two significant active RFID platforms. It is proved that power consumption with this new solution saves lots of energy when implementing ISO/IEC 18000-7 standard RFID protocol. Higher abstraction layers protocols can be implemented in future using this platform to obtain optimal active RFID solutions.

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Fig. 6: Power consumption savings analysis

References


