Lifecycle Extension of Long Range UHF RFID Tags based on Energy Harvesting

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Abstract **Recently applications of UHF RFID systems are often requiring sensing and monitoring capabilities on the transponder side as well as long operating ranges (long range sensor tag). Such functionality results in a high energy consumption of the tag on the one hand but also requires an uninterrupted energy supply on the other hand. This is not achievable with reader-powered passive UHF RFID Systems; an on-board energy source (battery) is necessary. Such energy store defines and limits the lifetime of a sensor tag, which is a key parameter specifying the reliability and the quality of this type of UHF RFID system. This paper describes the combination of special power saving techniques with novel energy storage structures incorporating energy harvesting devices to guarantee a reasonable lifetime of the resulting sensor tag architecture.**

I. INTRODUCTION

Nowadays pure passive RFID systems are used mainly for item and pallet tagging in the supply chain management. The demand on future UHF RFID tags (EPCglobal: class 3, class 4 [1]) is beyond the requirements of pure passive UHF RFID systems. Complex sensing and monitoring applications as well as the capability for complex computing tasks are required. Mean for communicating among each other (tag to tag communication) and independently form network topologies (ad hoc networking) will be necessary. A long range sensor tag satisfies a big part of those requirements and combines the low power design and communication technique of a passive UHF RFID tag with the advantage of a high operating range and sensing and monitoring capabilities. This is achieved by an on-board energy supply, which on the one hand guarantees a uninterrupted and stable energy supply (sensing and monitoring) and on the other hand provides the necessary energy for the operation of the tag itself (long operating range). The fact, that the energy needed by the tag for its operation is provided by the UHF RFID reader in pure passive UHF RFID systems ([2]) is the main limiting factor for the operating range, due to the high damping in the UHF frequency band.

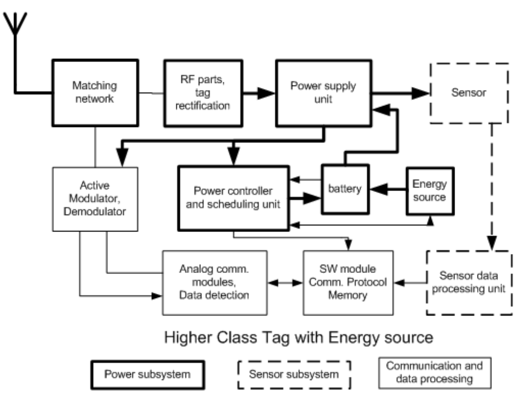

FIGURE 1 - ARCHITECTURE OF A LONG RANGE SENSOR TAG

Figure 1 shows the system structure of a long range sensor tag. The structure can be divided into three main subsystems: the power and scheduling subsystem, the communication and data processing subsystem and the sensing subsystem. The power subsystem, related power management techniques and the use of energy harvesting devices as power supply are the focus of this paper and will be discussed in the following sections.

II. NOVEL POWER SAVING TECHNIQUES

The duty cycle of a long range sensor tag depends strongly on the communication process as most actions are initiated by UHF RFID reader commands. Based on this considerations two main mechanisms for saving power can be considered.

2.1 Sleep state transition

The goal of this technique is, that the system stays in a low power (sleep) state as long as possible and switches to the active state only triggered by a certain event [3]. Typically the power consumption in the low power state is a few hundred times lower than in the active state (e.g. TI-MSP430x2xx: I Active mode = 3000*I lowest power mode [4]). This event may be a time tick signal or the output of a low power wake-up signal decoder. Such a decoder searches and recognizes a special wake-up bit pattern (preamble - [5]) in the digital data sent by the reader and triggers the wakeup event.

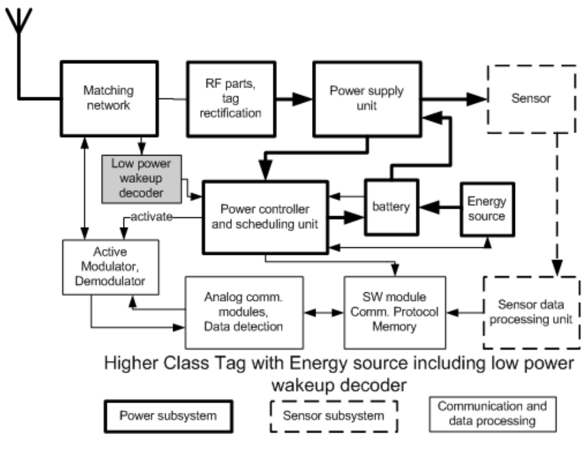

FIGURE 2 - STRUCTURE OF HCT INCLUDING LOW POWER WAKEUP DECODER

As shown at figure2 upon reception of the wake up signal pattern the low power decoder activates the main decoding block and the receiving state machine, which processes incoming communication sequences. Figure 3 describes the state machine handling the wakeup process. The application itself forces the tag to switch back to the sleep state if all tasks have been completed.

Figure 4 depicts an example of the structure of an activation command. In this case the wakeup procedure is based on the same technique as the reader to tag communication is done (data communication based wakeup) but the structure of the preamble is a pattern, that never appears within the normal communication data stream. This

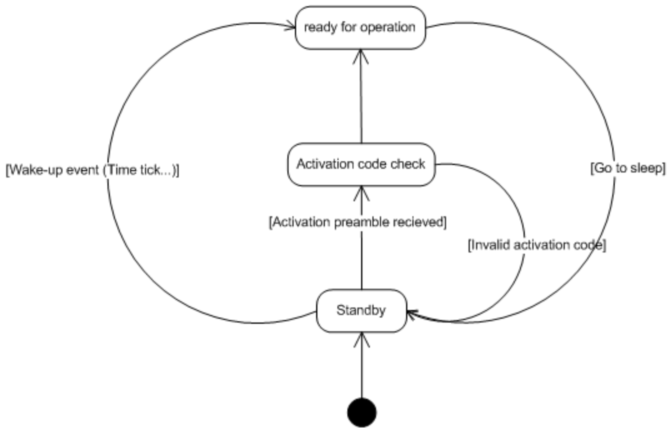

FIGURE 3 - STATEMACHINE OF THE WAKE-UP PROCEDURE [5]

is achieved by using a data rate, which is not supported in the communication process or by intentionally produced coding errors. The preamble itself is the most important part of the activation command forcing the tag to switch in the activation code check state. The low power wakeup code check mechanism checks the activation mask and if it matches, the tag is fully activated. The activation code structure shown in Figure 4 allows to wake-up all semi-passive tags in the range of the reader or just selective wake-up a certain target-subset of the tag population by using an activation mask. This mechanism is included in the ISO 18000-6REV1 UHF RFID Air interface communication protocol [5].

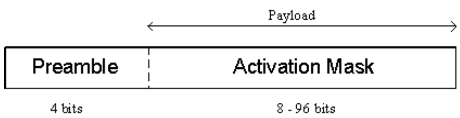

FIGURE 4 - EXAMPLE FOR A STRUCTURE OF AN ACTIVATION CODE [5]

The uniqueness of the preamble shown at Figure 4 is ensured because of the low data rate of 8kBit/s in comparison to the lowest data rate defined for the higher level(reader to tag) communication (40kBit/s). The maximum time required to wake-up a tag is 30ms (full 96bit activation code) but typically it is lower than 3ms (10 bit activation code).

2.2 Reader distance measurement

This power saving or even energy harvesting mechanism is based on the evaluation of the distance between tag and reader. It may be done by simply measuring the strength of the received reader signal (carrier) or determine the distance with distance evaluation mechanisms.

Depending on the distance between tag and reader, three different operating modes can be defined (see figure 5).

1. The first mode applies if the distance of the tag to the reader is short enough that the tag can be powered by the energy provided by the reader carrier signal. The operation does not require the support of the on board battery, which is disconnected. The distance for this case is typically around 5m.

2. The second mode applies if the distance is typically between 8m and 20m. The tag can not be powered by the reader signal due to the high distance but the communication with the reader is still possible. The battery is used for powering the tag.

3. The third mode applies if the distance to the reader is too high for communicating, the reader wound be able to demodulate the data transmitted by the tag. The tag is powered by the battery but it does not respond to received reader commands. The distance in that case is typically higher than 20m.

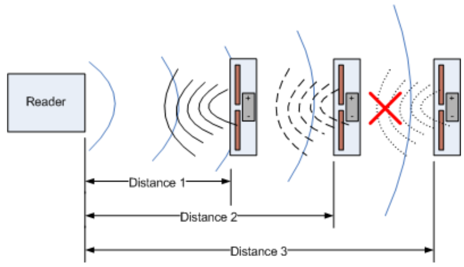

FIGURE 5 - READER DISTANCE MEASUREMENT: THREE-MODE-ALGORITHM

This three-mode-algorithm based on the reader distance measurement allows to save a high amount of energy by simply taking into account the energy, provided by the reader. The performance of the algorithm has been evaluated by simulating various identification scenarios. The results show an energy saving of 50% under certain conditions (see [6]).

III. NOVEL ENERGY STORAGE STRUCTURES INCLUDING ENERGY HARVESTING DEVICES

Energy harvesting devices are able to provide a small but continuous amount of energy and thus support the tags on-board energy reservoir significantly. This corresponds mainly to the relatively low, but permanently consumed standby energy when the tag is in the low power state ([6]). On the other hand, the energy provided is unstable, non-continuous and hard to predict [6] requiring special interfacing and energy storage structures.

The energy storage structure contains the energy harvesting device (e.g. solar cell), a primary battery and the secondary buffer structure (ultracapacitor [7]) as well as a control unit. The control unit monitors the state of charge and the power supplied by the energy harvesting devices and connects the components. The buffer unit (ultracapacitor) is necessary, because of the strongly fluctuating energy provided by the energy harvesting device and the non-deterministic peak power consumption of the sensor tag depending on external events (communication, reader commands) and internal activities (writing to memory). The primary battery finally guarantees a certain lifetime even if the power provided by the harvesting device is very low.

IV. NOVEL APPROACH: ENERGY STORAGE STRUCTURE SIMULATION MODEL

The performance of various implementations of energy storage structures has been simulated and compared. The following figure 6 shows the structure of the simulation model used, which has been implemented based on MATLAB Simulink®. The power consumption of the sensor tag (measured using a state-of-the-art sensor tag from Identec Solutions [8]), as well as the power supply (Solar cell - SP3-37 [9]- measured as described in [6]) have been modeled as pre-measured power profiles. The primary battery was represented by a stochastic battery model (see [10]) based on datasheet parameters from the real battery, the ultracapacitor as a simpler behavioural model.

The simulations have been done comparing the simulated lifetime of the mentioned state-of-the-art long range sensor tag to a virtual, simulated tag equipped with the proposed energy storage structure(see [11]).

Figure 7 shows the implementation variant, which produced the best simulation result. It completely decouples the primary battery from the tag. The structure includes three ultracapacitors being alternately charged and discharged. The charging is done by the primary

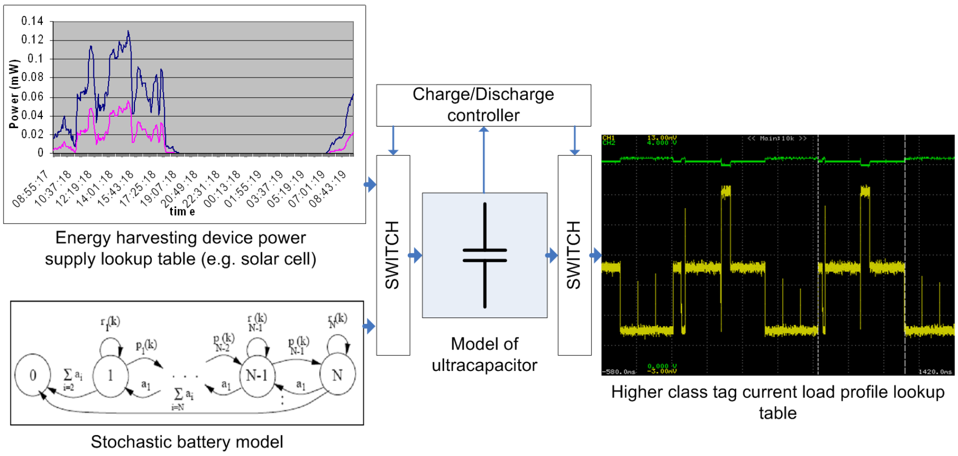

FIGURE 6 - STRUCTURE OVERVIEW OF THE SIMULATION MODEL

battery or by the energy harvesting device (solarcell SP3-37 [9] in this case). The use of three ultracapacitors guarantees, that always one of them is able to provide the power for the tags operation. This guarantees a highly efficient use of the energy provided by the harvesting device.

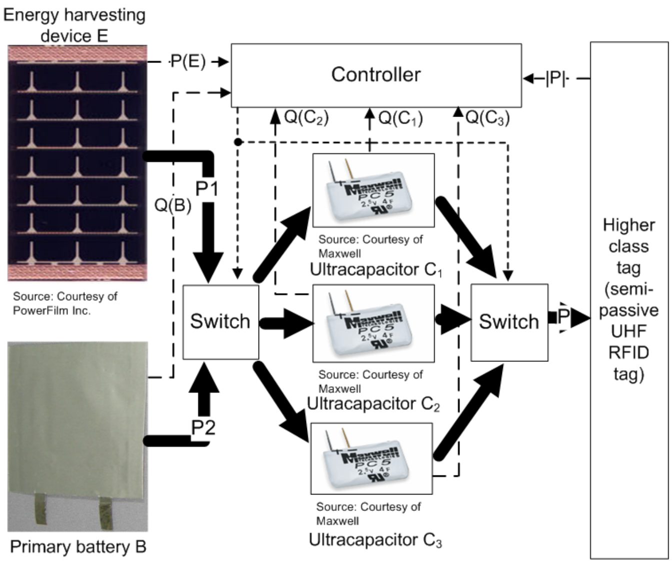

FIGURE 7 - ENERGY STORAGE STRUCTURE - IMPLEMENTATION VARIANT

V. SIMULATION RESULTS

The results of the simulations mentioned bfeore and in [6] have shown a significant reduction of the power consumption of the tag applying proposed power saving mechanisms (-50% power consumption). Additionally it was shown that the lifetime of the tag will be significantly extended by using the proposed energy storage structures (e.g. figure 7). Table 1 summarizes related simulation results.

Method	Improvement
Power saving techniques [6]	-50% power
Energy harvesting devices and Energy storage structures [11] - structure shown in Figure 7	+44% lifetime

TABLE 1 - SUMMARIZED SIMULATION RESULTS

VI. VERIFICATION THROUGH PROTOTYPE IMPLEMENTATION

The simulation model mentioned in the section before has been implemented as a hardware prototype including all modeled parts to verify the correctness of the simulation results. As the goal of the implementations of today's sensor tags is to achieve a very high lifetime, it was not possible to prove the identical power subsystem structure in the real implementation. The time required for the measurements would have been to long (approximately seven years). For verification purposes, the capacity of the primary battery as well as of the ultracapacitors has been reduced compared to the mentioned state-of-the-art sensor tag and the tag's current consumption profile has been replaced by a constant discharge current. The identical components have been used in the simulation model (including the measured values of the solar cell) to enable a direct comparison of the results. Figure 8 and figure 9 are comparing the simulation model with the hardware prototype of the energy storage structure. The blocks of the structure are:

1. Solar cell SP3-37 (hardware prototype) as well as the measured current values (simulation)
2. Charge/Discharge control microcontroller MSP430 (hardware prototype) as well as the same controller statemachine - MATLAB/Simulink® Stateflow (simulation)
3. Ultracapacitors (3*0.1F)
4. Primary battery (Maxell CR2032, 230mAh) - stochastic battery model (simulation) using datasheet parameters, real battery (prototype)
5. Discharge current setting (constant discharge current)
6. State Of Charge (SOC) of the battery and simulation time counters (simulation model only)

6.1 Verification results

The results of the verification are shown at table 2. Inaccuracies came from partly missing battery parameters and the unknown initial charge capacity deviating from the nominal charge capacity of batteries. The nominal capacity as stated by the battery manufacturer is used in the simulation model. Anyway the simulated lifetime comes very close to the lifetime of the real implementation (-4,2% error). Therfore it has been verified, that the simulation model allows an accurate estimation of the expected lifetime of the tag.

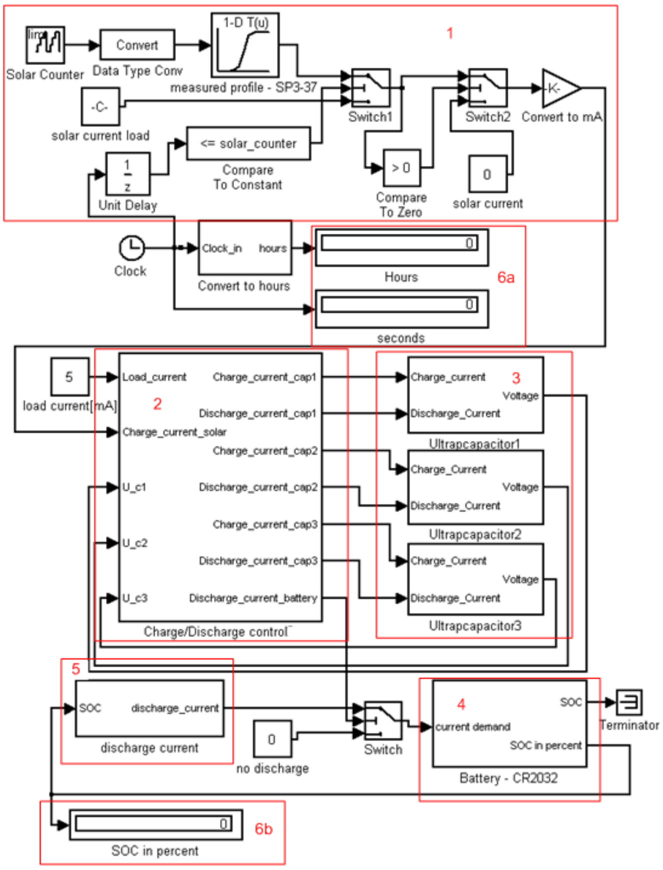

FIGURE 8 - SIMULATION MODEL USED FOR THE VERIFICATION WITH BLOCK NUMBERING AS MENTIONED IN VI.

Implementation	Lifetime	Error
Simulation model variant 3 (figure 8)	112 hours	-4.27%
Prototype implementation variant 3 (figure 9)	117 hours	-

TABLE 2 - SIMULATION ACCURATENESS VERIFICATION RESULTS

VII. CONCLUSION

The performance of using special power saving techniques as well as energy harvesting devices and related energy storage structures for the improvement of the lifetime of a long range sensor tag has been evaluated and simulated. The simulation results have been verified by comparing simulated results to an identical prototype implementation. This verification has shown a high accuracy of the simulation results with an error of -4.2%. The results of the so verified simulation model have shown the possibility of a significant extension of the lifetime by applying proposed novel power saving mechanisms (-50% power consumption) and using proposed novel energy storage structures (up to 44% longer lifetime) incorporating energy harvesting devices.

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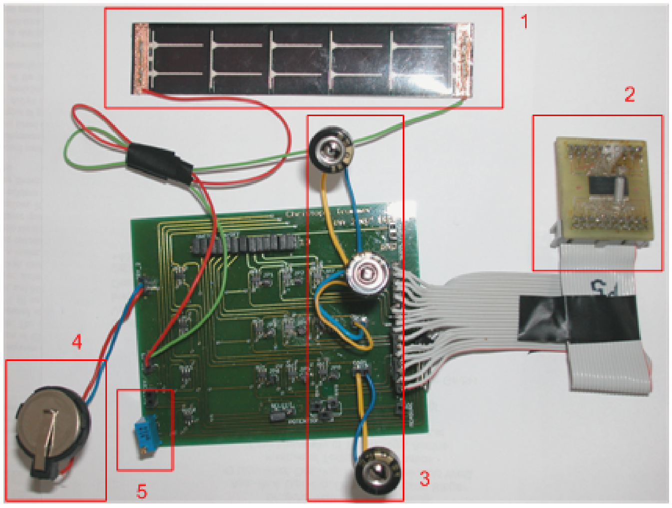

FIGURE 9 - STRUCTURE OF THE PROTOTYPE IMPLEMENTATION WITH BLOCK NUMBERING AS MENTIONED IN VI.

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