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Protocols for Active RFID – The Energy Consumption Aspect

Björn Nilsson, Lars Bengtsson, Per-Arne Wiberg, and Bertil Svensson

Abstract—The use of Radio Frequency Identification systems (RFID) is growing rapidly. Today, mostly “passive” RFID systems are used because no onboard energy source is needed on the transponders. However, “active” RFID technology, with onboard power sources in the transponders, gives a range of opportunities not possible with passive systems. To obtain energy efficiency in an Active RFID system the protocol to be used should be carefully designed with energy optimization in mind. This paper describes how energy consumption can be calculated, to be used in protocol definition, and how evaluation of protocol in this respect can be made. The performance of such a new protocol, in terms of energy efficiency, aggregated throughput, delay, and number of air collisions is evaluated and compared to an existing, commercially available protocol for Active RFID, as well as to the IEEE standard 802.15.4 (used e.g. in the Zigbee medium-access layer).

Keywords—Active RFID; Protocol; Energy efficiency

I. INTRODUCTION

Automation in logistics has driven the development of Radio Frequency Identification (RFID) in the past years. Scenarios for RFID might for instance be in the logistic chain, tracking goods from the producer to the consumer, where the goods can be a single product or up to several hundred products on a single pallet. Items must be identified fast by the RFID-reader when e.g. a fork lifter transports them and passes an RFID-reader. In this realm, RFID could also be used for automatic inventory of the stock at a warehouse, where there are no critical reading delays but a huge amount of tagged goods to identify.

Mostly “passive” (meaning that the transponder, also called “tag”, has no power source of its own [1]) RFID technology has been in focus, but recently also “active” (where the tag has an onboard battery) RFID [2, 3] has gained more interest [4, 5]. By using an onboard power source for the tag, a wide range of new applications are enabled. There are several advantages of using an onboard power source. An active tag is able to gather sensor

information and store it for later delivery to an RFID-reader (in some literature the RFID-reader is referred to as an interrogator). Also, reading-range and -directivity is improved compared to passive RFID, because of higher output power from the transmitting tag and also because a more sensitive receiver can be constructed in the tag. The drawback is that the use of active circuits limits the life time of the active tag compared to the passive one. The wireless RF-link is the part that consumes most of the power. Therefore, to achieve longer battery life-time for an active tag, an energy efficient protocol for Active RFID must be used.

This paper compares four protocols for Active RFID regarding energy efficiency: 1) Free2move’s protocol which is based on Frequency Hopping Spread Spectrum and Time Division Multiple Access (hereafter called the “current protocol”). It uses two different modes which can be chosen to fit the application. 2) An enhanced protocol which is based on the Free2move current protocol (hereafter called the “enhanced protocol”), but with enhancements that make more use of the radio channel. 3) 802.15.4 (Zigbee MAC-layer), used as a contention based slotted protocol. 4) A fictive “reference protocol”, a protocol which is optimized with the same constraints in the radio channel as the Free2move protocols but assuming that no energy is needed to detect an RFID-reader (hereafter called reader).

The paper is organized as follows: First we describe the general requirements in Active RFID-systems. Section III then presents some existing protocols as well as how the Medium Access Layer in 802.15.4 could work when used as an Active RFID protocol. In Section IV we show a comparison of protocol performance in the form of results from simulations in terms of throughput and payload packet delay. In Section V the energy consumption of a tag executing the protocols is examined, and we show expressions for calculating energy consumption. The energy efficiency and energy consumption of the protocols are compared in Section VI. This section also shows the life time of a tag when using a commercially available battery cell as onboard power source. Conclusion and discussion are presented in Section VII.

II. ACTIVE RFID SYSTEMS

There is an increasing interest in the RFID field right now. A standardization effort has successfully been carried out and the Electronic Product Code (EPC) Generation 2 tags

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[6] have been launched on the market. Big players like Wal-Mart and other retail companies are introducing the technology in their supply chain management.

An RFID tag can be viewed as an electronic bar code, with the difference that information can be written to the tag a number of times and that a reader can read the tag from a distance of up to 2 meters.

A passive tag is powered by the radio frequency field generated by the reader. This has the obvious advantage that no battery is needed. This has an impact on lifetime and cost. The lifetime of a passive tag can be said to always be longer than the usage time. The transceiver in the tag is implemented on one silicon die, yielding a cost below 10 US cents. There are, however, some troublesome disadvantages with Passive RFID-systems.

Passive tags use backscattering to transmit information from the tag to the reader. In order to make this work, the reader has to radiate very high levels of radio energy. Also, when many readers are operating in proximity of each other there is severe interference between them. Another disadvantage is the fact that the tag cannot perform any operation when it is outside the range of a reader, such as e.g. temperature logging. These disadvantages have led to the need for tags that are powered by a power source, typically a battery.

These systems are referred to as Active RFID-systems. In such systems the tag is equipped with a radio transceiver, and the communication with the reader conforms to a protocol. There are some specific requirements on both the hardware architecture and the protocol for these Active RFID-system requirements that differ from other communication devices, such as those found in sensor networks.

The RFID application requires fast access to many tags. The tag address is often unknown to the reader prior to the access. Therefore, some type of device discovery mechanism is needed in the protocol. We have this need in sensor networks as well, but in many applications proposed for e.g. Zigbee [7], like house automation, the network structure is static. A static network structure can have a configuration mode gathering addresses and setting up the communication pattern. However, this is not possible in our scenario.

The energy consumption is a critical parameter in an Active RFID-system. A tag is basically in one of two states: within range of a reader or out of range of a reader. A tag must be able to operate in an energy efficient way in both of these states. The protocol needs to support changes in the wake-up cycle, which is how often a tag wakes up from sleep-state and is able to be discovered by or discover a reader. Further in the text the wake-up cycle is referred to as a "cycle". Choosing the duration of the cycle is a trade-off between keeping the energy consumption low and having an acceptable latency in the discovery by the reader.

The requirements on the network topology differ also between RFID-systems and sensor networks. Active RFID is, as mentioned above, a very connection oriented application and the topology can be viewed as a highly dynamic star topology. A sensor network, on the other hand,

is often viewed as a multi-hop network that can be either dynamic or static. This calls for other functionality in the protocol, for example for routing. Also, as shown in [8], by, for example, using asymmetric coding, a well designed single hop network which perform better than a multi hop network, in terms of overall power consumption.

In this paper we explore differences between two protocols used in Active RFID-systems. One of them is a protocol used in an Active RFID-system developed by the company Free2move, and the other one is the MAC-layer of Zigbee (standard IEEE 802.15.4.). The two protocols are designed to fulfill somewhat different requirements. The Free2move protocol is made for Active RFID while the Zigbee protocol was originally designed with sensor networks in mind.

III. EXISTING ACTIVE RFID PROTOCOLS AND STANDARDS

There is up to this date no commonly agreed standard set for Active RFID protocols, although ISO 18000-7 [9] defines the air interface for RFID devices operating as an active tag in the 433MHz band used in item management applications. Its purpose is to provide a common technical specification for RFID devices that may be used by ISO committees developing RFID application standards. Implementation of ISO 18000-7 [10] shows rather low performance regarding throughput and delay compared with the protocols presented in this paper. However, there exist many proprietary protocols specialized for different tasks in automation and logistics.

This section describes three protocols in some detail: 1) The current, 2) The enhanced, and 3) 802.15.4. A more detailed description of the current and the enhanced protocols can be found in [11]. Also a fictive reference protocol is used for comparison of what would be possible using the same radio circuits and the same amount of bandwidth in the 2.45 GHz ISM band as used by Free2move's RFID-system [12] and circuits available on the market supporting the 802.15.4 standard [13]. The reference protocol does not need any energy to detect a reader and wake up.

A. The current protocol

The existing Free2move protocol works either in a synchronized (slotted ALOHA [14] like) or a non-synchronized (ALOHA like) system mode. In the synchronized mode (also called RTF, "Reader Talks First"-mode) the reader sends beacon signals on which tags react, while in the non-synchronized mode (also called TTF, "Tag Talks First"-mode) tags react independently of the reader. None of the modes represents collision free schemes; rather they are both examples of contention based schemes [14].

A tag typically works in a periodic way, waking up and releasing information to the reader and then entering sleep mode again. In the RTF-mode the reader continuously sends beacon signals to create a slotted scheme. The frame size is always the same but, as shown in earlier work [15], it can be changed to get higher throughput. Between the beacon signals the reader listens for answers from the tags. The

reader is able to listen to two frequency channels at the same time and receive information from two tags that are synchronized with the reader beacon signal. When answering, the tag randomly chooses one of the two frequencies. Also the reader switches between and transmits on two different channels. The methods used are similar to a limited frequency hopping spread spectrum scheme (FHSS).

In the TTF mode a tag wakes up randomly and delivers information to the reader on one out of four possible frequencies, without being synchronous with the reader. These four frequencies are divided into two groups, and on each group information from two simultaneously transmitting tags can be received at the same time. Due to the absence of synchronization between tags, the first recognized tag (on one of these group-frequencies) is read by the reader, while the second first (on this channel) is excluded from a read. This is a ‘first come first served’ (and also only to be served) technique.

Both TTF and RTF allow tags to be reconfigured in terms of functionality (shifting between RTF and TTF, being sensor node or pure ID node) by being directed to a scheduled FIFO queue; this is done by the reader on a special configuration channel.

Free2move’s two different approaches, RTF and TTF, are included in one protocol. By using user configurations the protocol is able to be adjusted to fit a wide range of applications in logistics and automation, such as flight transports, where a tag preferably would be in RTF and only listening, not emitting any RF-energy that can disturb the plane. When leaving the airplane the tag enters TTF because multiple, non-interfering readers are used. This reconfiguration works on the fly, meaning that the reader can adapt the tag to the scenario and application at hand.

B. The enhanced protocol

Conclusions from early simulations [11] led us to add features in the current protocol to further improve its performance. The most important modification was to include a “deep-sleep” parameter in the acknowledge message from the reader. This parameter tells the tag to enter a deep-sleep mode for a variable time specified by the reader. The second improvement is an enhanced utilization of the radio channel in RTF by using all available slots for beacon signals and not every second on different channels as in the current protocol. These enhancements lower the energy consumption considerably; for example, during the time when the reader is available and when the tag is set to deep-sleep for ten seconds after successfully delivering its payload to the reader, the energy consumption is reduced with 90%. When there is no available reader in the vicinity, the energy consumption is lowered with 34% (when using a cycle of one second) because of the reduced time needed to listening for a beacon signal.

Figure 1 shows how a tag executes in the two different enhanced modes to deliver a packet to a reader. It shows the tag’s behavior both when a reader is available and when no reader is available. It also shows the working of the reference protocol. The most efficient one (regarding the energy

efficiency) is of course executing the reference protocol, because the sleep state and the deep-sleep state are states where hardly any energy is consumed.

Figure 1. Tag executing different modes in the enhanced protocol when no reader is available and when there is one.

C. IEEE 802.15.4

An existing radio technology that is a supposed nominee for Active RFID is the IEEE 802.15.4 standard [16]. It is part of the IEEE 802.15.x suite, aimed for wireless personal area networking. The IEEE 802.15.4 specification supports short range, low rate and low power radio interconnection of electronic devices.

The physical layer is based on direct sequence spread spectrum (DSSS) and is available in two flavors; the first version operates in the 868/915 MHz ISM band and the second version in the 2.45 GHz ISM band. The 868 MHz (Europe) and 915 MHz (U.S.) version supports a raw bit-rate of 20/40 kbit/s, and the 2.45 GHz version (worldwide) supports a raw bit-rate of 250 kbit/s over the radio link. Two different network topologies are supported: a peer-to-peer topology and a star topology. The star topology is suitable for Active RFID applications, and is built out of two types of devices: the full functioning device (FFD) and the reduced functioning device (RFD). A star topology must contain at least one FFD, the so called coordinator. In Active RFID applications, the reader is an FFD device (coordinator) and the RFID tags are RFDs.

Contention based and contention free channel access is supported by IEEE 802.15.4. For Active RFID applications the contention based channel access mechanism is preferable since the number and identities of tags in range of the reader (coordinator) change over time, i.e., resource allocation is of no use if the target is to deliver the device ID (or some other small amount of data to the reader) only once.

The contention based channel access mechanism is based on a distributed slotted/non-slotted carrier sense medium access method with collision avoidance (CSMA-CA) back off algorithm. If slotted CSMA-CA is used, the coordinator sends a beacon, for example every 16th slot, to synchronize all units. When a tag wakes up, it first listens for the beacon, and when the tag finds the beacon it waits for a random

back-off time (aligned with the slot boundaries). After the random back-off time has passed the tag acquiring the channel performs carrier sense, and if the channel is free it starts the transmission.

If non slotted CSMA-CD is used, the tag wakes up, waits for a random back off time, and performs carrier sense. If the channel is sensed free, the tag starts the transmission. All transmissions can optionally be acknowledged, if requested by the application.

IV. COMPARISON OF PROTOCOL PERFORMANCE

This section compares the performance in terms of throughput and payload packet delay. The reference protocol is used for comparison.

A. Simulation method and results

All simulations begin with the user population of 50 tags available to the reader. Simulations are then done for an increasing number of tags until reaching 3000. The cycle time is set to one second. The channel is assumed to be of the errorless collision type. The propagation time for packets to and from the reader is assumed to be zero. Figure 2 shows a comparison of throughput, measured as the number of tags that were successful in delivering one payload packet during one cycle. Every tag wakes up during a cycle, at a time which has a uniform random distribution. The curve for the reference protocol coincides with that for the enhanced RTF and has the highest throughput (upper curve). The 802.15.4 (second upper curve) also shows high throughput, with a peak at 800 tags. Compared to the current TTF the enhanced TTF (bottom curve) has a much lower throughput (almost halved). The reason for this behavior is that the enhanced TTF utilizes more of the radio channel. The reader transmits an acknowledge packet, which is not done in the current TTF.

Figure 2. Aggregated throughput when executing different protocols. Enhanced RTF and Reference coincide.

Figure 3 shows the delay (message delay) for all protocols and protocol-modes. The curves for the current TTF and RTF (the two left-most curves) raise rather quickly,

resulting in a long delay already when only a small amount of tags are in the proximity of a reader. The enhanced RTF (the third fastest rising curve) is much improved compared to the current one. The 802.15.4, the enhanced RTF and the reference protocol are close together in the bottom of the diagram, i.e., showing short delay. There is a marginally higher efficiency in the 802.15.4 when the number of tags is smaller, below 1400, in the proximity of the reader. This is a result of using carrier sense, but when increasing the number of tags this is not enough. The acknowledge packet in 802.15.4 can not contain any additional information, and thus can not be used to set the tag to deep-sleep for a variable number of cycles. Therefore, the delay can not be kept at a more flat level for a large number of tags.

Figure 3. Delay for tag when executing different protocols. Enhanced RTF and Reference coincide.

V. CALCULATIONS OF ENERGY CONSUMPTION

This section is devoted to the energy consumption of a tag executing different protocols. The energy consumption further depends on if there is an available reader or not, as well as on the number of tags accessible by the reader. The energy consumption is described in terms of Joule per cycle. The cycle time used in calculations and tables in this section is set to one second.

A. The current protocol and the enhanced protocol

In this section, expressions that describe energy consumption in the current and the enhanced protocols are presented. Two different situations are covered: when there is a reader in the vicinity and when there is not.

There are four states in which a tag can operate. The sleep-state is when a tag is inactivated and only an internal timer is running, for periodic wake up purpose. This state consumes very little power. The running state, when tags make calculations and set the transceiver in different states, executes at a rather low frequency (typically a few MHz). The energy consumption in the transmit (TX) and the receive states (RX) are dependent on the characteristics of the transceiver. Free2move's tag uses a transceiver in the GHz range with a moderate bit rate (250 kbit/s) and it has a

working range of up to 50 meters in free space. The output power is maximum 0 dBm (1 mW), the sensitivity is approximately -90 dBm, and the channel spacing is 1 MHz. The power consumption for TX is lower than for RX. Measurements on the circuits used in the Free2move tag show that TX uses about two thirds of what RX consumes. This also suggests that a protocol should spend as little time as possible in RX.

By combining the four described states, terms (table 1, column 1) for the forthcoming expressions can be defined. For example, to receive a beacon signal from the reader in RTF, the tag operates in both running-state and receive-state. The term in this case is called $\bar{E}_{Beacon}$ and describes the energy consumption for this action. This and other terms are shown in Table 1 and are extracted from circuit data sheets as described earlier. It is also possible to read from the table how much power the action consumes and for how many milliseconds it lasts.

Table 1 Terms, power, duration time, and energy used in the expressions.

term	power consumption [mW]	duration time [ms]	energy consumption /cycle [Joule]	explanation of energy consumption
Current RTF				
$\bar{E}_{Beacon}$	57	5	0.274	average energy consumption to receive a beacon signal, reader available
$\hat{E}_{Beacon}$	57	8	0.456	energy consumption when trying to receive a beacon signal, no reader available
E_{RX}	57	2	0.114	energy consumption to receive a packet
E_{TX}	42	2	0.067	energy consumption to transmit a payload packet
E_{Sleep1}	0.011	992	0.011	energy consumption when sleeping rest of a cycle after communication with a reader
E_{Sleep2}	0.011	992	0.011	energy consumption when sleeping rest of a cycle after trying to receive a beacon signal
Current TTF				
E_{RX}	57	2.0	0.114	energy consumption to receive a packet
E_{TX}	42	1.6	0.067	energy consumption to transmit a payload packet
E_{Sleep1}	0.011	996	0.011	energy consumption when sleeping rest of a cycle after communication with a reader
E_{Sleep2}	0.011	996	0.011	energy consumption when sleeping rest of a cycle after trying to receive a payload packet
Enhanced RTF				
$\bar{E}_{Beacon}$	57	3.4	0.194	average energy consumption to receive a beacon signal, reader available
$\hat{E}_{Beacon}$	57	5.2	0.296	energy consumption when trying to receive a beacon signal, no reader available
E_{Ack}	57	2.0	0.114	energy consumption to receive an acknowledge packet
E_{TX}	42	1.6	0.067	energy consumption to transmit a payload packet
E_{Sleep1}	0.011	993	0.011	energy consumption when sleeping rest of a cycle after communication with reader
E_{Sleep2}	0.011	995	0.011	energy consumption when sleeping rest of a cycle after trying to receive a beacon signal
$E_{Deep-sleep}$	0.011	1000	0.011	energy consumption when sleeping for a whole cycle
Enhanced TTF				
E_{Ack}	57	2.0	0.114	energy consumption to receive an acknowledge packet
E_{TX}	42	1.6	0.067	energy consumption to transmit a payload packet
E_{Sleep1}	0.011	996	0.011	energy consumption when sleeping rest of a cycle after communication with a reader
E_{Sleep2}	0.011	996	0.011	energy consumption when sleeping rest of a cycle after trying to receive an acknowledge
$E_{Deep-sleep}$	0.011	1000	0.011	energy consumption when sleeping for a whole cycle

A tag executing RTF must listen for a beacon signal. Table 1, column 3 shows how much time is needed for a tag, in average, to find a beacon signal when there is a reader in the vicinity. When there is no available reader the maximum listening time for a beacon signal is used instead. The energy consumed in sleep- and deep-sleep-state are the same and is

included in the expressions, and they only add a fraction of the total energy consumption (a factor 10,000 lower than for RX). The longer the cycle time is (here set to one second), the more important is it for the sleep- and deep-sleep states to consume low power. This is because the deep-sleep state becomes the longest part of the cycle and, for very long cycles, also the most power consuming. The term Ack in expressions is a variable that tells how many cycles the tag should stay in “deep-sleep” after a successfully transmitted packet in the enhanced protocol. This is application dependent; in the calculations the value of Ack is set to 10. Expression (1) shows the energy consumption during one cycle when a tag executes the current RTF and a reader is available.

$$E_{RTF \text{ current}} = \bar{E}_{Beacon} + E_{TX} + E_{RX} + E_{Sleep1} = 0.466 \text{ mJ} \quad (1)$$

$$E_{RTF \text{ enhanced}} = \bar{E}_{Beacon} + E_{TX} + E_{Ack} + E_{Sleep1} = 0.386 \text{ mJ} \quad (2)$$

The enhanced RTF (2) yields 17% lower energy consumption than the current RTF. When including the deep-sleep-mode (3 & 4) the energy will be 90% lower in the best case (when $Delay=1$).

$$E_1 = \bar{E}_{Beacon} + E_{TX} + E_{Ack} + E_{Sleep1} \quad (3)$$

$$E_{RTF \text{ enhanced}} = \frac{E_1 \cdot Delay + E_{Deep-sleep} \cdot Ack}{Ack + Delay} = 0.045 \text{ mJ} \quad (4)$$

The $Delay$ term is dependant on the number of tags occupying the radio channel. In the above expressions this term is set to 1, indicating no delay for packet delivery (tags successfully deliver a packet to the reader at first try). This is true for a small number of tags in the vicinity of a reader. The value of $Delay$ can never become less than 1, because the tag execution is cyclic and needs at least one cycle to deliver a packet.

When no reader is available the execution of the current protocol only includes time spent listening for a reader. The same holds for the enhanced one. The enhanced protocol offers 34% lower energy consumption, shown in (5) and (6)

$$E_{RTF \text{ current}} = \hat{E}_{Beacon} + E_{Sleep2} = 0.467 \text{ mJ} \quad (5)$$

$$E_{RTF \text{ enhanced}} = \hat{E}_{Beacon} + E_{Sleep2} = 0.307 \text{ mJ} \quad (6)$$

For TTF there is no possible improvement like in RTF when there is no accessible reader. Still expression (6) compared to (7) shows (Where (6) is enhanced RTF with no available reader, and (7) is TTF with no available reader.) that TTF is the most efficient one in terms of energy consumption.

$$E_{TTF \text{ current}} = E_{TX} + E_{RX} + E_{Sleep1} = 0.192 \text{ mJ} \quad (7)$$

$$E_1 = E_{TX} + E_{Ack} + E_{Sleep1} \quad (8)$$

The energy consumption for enhanced TTF if there is an available reader shows (8 & 9) an 85% improvement when including deep-sleep.

$$E_{\text{TTF enhanced}} = \frac{E_1 \cdot \text{Delay} + E_{\text{Deep-sleep}} \cdot \text{Ack}}{\text{Ack} + \text{Delay}} = 0.028 \text{ mJ} \quad (9)$$

The improvement for TTF when there is an available reader is scalable with the *Ack* factor. This is true as long as the power consumption for deep-sleep, described by the term $E_{\text{Deep-sleep}}$, is lower than the average energy consumption of RX and TX added over one cycle. As for Enhanced RTF, there is a delay term that must be added which is dependent on the number of tags occupying the radio channel. As in Section IV, the delay increases when the number of tags in the vicinity of a reader increases.

The drawback of inferring the *Ack* term in both RTF and TTF is that the response time, the time it takes to find the tag, increases with the same factor. The value of the *Ack* can be chosen to fit the application needs. The term *Delay* for RTF will increase rather slowly compared to *Delay* for TTF in the enhanced protocol. This shows that for applications using a large amount of tags, the choice should be RTF.

B. Energy consumption for 802.15.4

In this section, expressions for the energy consumption when using a contention based 802.15.4 protocol are presented. Figure 4 shows how a tag executes to deliver a packet to a reader, both when a reader is available and when no reader is available. The tag periodically searches for a beacon signal. If no beacon is found it returns to sleep mode. When finding a beacon signal the tag makes a back-off for a random time and then performs a carrier sense. If no other carrier is sensed, the tag transmits its payload packet, waits for acknowledge from the reader, and then returns to sleep until the next cycle starts. Since there is no room for additional information in the acknowledge message, it is not possible for the reader to decide, when using the 802.15.4, if the tag should enter deep-sleep-mode and for how long. The 802.15.4 would require communication with multiple packets to be able to do so, and it is only possible from an application.

Figure 4 Tag executing 802.15.4 and the reference protocol.

The calculated energy consumption of an 802.15.4 based transceiver, like the CC2430 chip from Chipcon/Texas instruments, is shown in Table 2. The table is constructed in the same way as described for the current- and the enhanced-protocols. This transceiver offers 250 kbit/s data rate, 0 dBm output power and a sensitivity of -94dBm. The channel spacing is 5 MHz and the bandwidth is 2 MHz.

Table 2. Terms, power, duration time, and energy used in the expressions.

term	power consumption [mW]	duration time [ms]	energy consumption /cycle [Joule]	explanation of energy consumption
802.15.4				
$\bar{E}_{\text{Beacon}}$	81	7.7	0.622	average energy consumption when trying to receive a beacon signal, reader available
$\hat{E}_{\text{Beacon}}$	81	15.4	1.244	energy consumption when trying to receive a beacon signal, no reader available
E_{Ack}	81	0.32	0.026	energy consumption when receiving an acknowledge from a reader
E_{CS}	81	0.13	0.011	energy consumption when doing a carrier sense
E_{TX}	75	1.6	0.120	energy consumption when transmitting one payload packet to a reader
E_{sleep1}	0.003	990	0.003	energy consumption when sleeping after successfully delivered payload to a reader
E_{sleep2}	0.003	992	0.003	energy consumption when sleeping after no successfully delivered payload to a reader
E_{sleep3}	0.003	985	0.003	energy consumption when sleeping after listening for a beacon, no reader available

The 802.15.4 based tag executes in a cyclic manner (one second cycle) as described earlier. Expression (12) shows the energy consumption of a tag when a reader is available and the *Delay* is set to 1. The number of back-off tries in the best case is 1 (maximum 3) when a packet is successfully delivered. The worst case is when there are 3 back-offs. The case when there is no available RFID-reader is described by (13). (10) shows the energy consumption for listening for a beacon (and finding one), making carrier sense tries 3 times without succeeding to find a free space in the radio channel in order to deliver a payload packet. The energy cost to find a beacon and successfully deliver a payload packet is shown in (11). (10) and (11) are then used in (12). The expressions show that, when there is no available reader, the tag uses 33% more energy than when there is a reader.

$$E_1 = \bar{E}_{\text{Beacon}} + E_{\text{CS}} \cdot 3 + E_{\text{Sleep1}} \quad (10)$$

$$E_2 = \bar{E}_{\text{Beacon}} + E_{\text{CS}} + E_{\text{TX}} + E_{\text{Ack}} + E_{\text{Sleep2}} \quad (11)$$

$$E_{802.15.4} = \frac{E_1 \cdot (\text{Delay} - 1) + E_2}{\text{Delay}} = 0.78 \text{ mJ} \quad (12)$$

$$E_{802.15.4} = \hat{E}_{\text{Beacon}} + E_{\text{Sleep3}} = 1.3 \text{ mJ} \quad (13)$$

VI. ENERGY CONSUMPTION

This section shows results in energy efficiency and energy consumption in an Active RFID system. Two aspects will be looked upon, namely the energy cost of delivering the payload [17] and the battery life time of a tag. Energy efficiency is described in terms of energy in Joule per successfully transmitted payload bit (J/bit) as well as in terms of the battery life time when draining a tag battery cell –this is measured in number of days. The reference protocol is used for comparison of what is possible when using the same radio circuits and the same bandwidth as described earlier. The calculation of the energy consumption must consider if there is an available reader or not, as well as the number of tags accessible by the reader.

When a tag executes different protocols in different modes, some of them always consume a constant energy, like the current RTF and TTF, even though the number of tags increases in the proximity. When a tag tries to deliver a payload packet to a reader the delay parameter, described earlier, must be included. Figure 5 shows the growth of the energy consumption when the number of tags in reach of the reader increases. The enhanced RTF (bottom curve) shows great improvements but for enhanced TTF (dotted curve) the improvements are moderate. The 802.15.4 based protocol (third curve from bottom) also shows good results compared to the different modes of the current protocol.

Figure 5. Energy consumption when executing different protocols.

The total energy consumption when there is an available reader is shown in Figure 6. The 802.15.4 (upper curve) shows higher total energy consumption. The enhanced variants of RTF and TTF (second and third bottom curves) show lower total energy consumption because the tag uses the deep-sleep mode after a successfully delivered payload packet. Current RTF (second upper curve) shows constant energy consumption but the tag has no knowledge what so ever if a payload packet has reached the reader or not. The same is true for the current TTF (lower straight line).

When there is no available reader the total energy consumption is constant for all the protocols. The life time of a tag can easily be calculated and be described in days, as shown in Table 3.

Table 3 Total energy consumption when no available reader is present, and life time when executing different protocols.

protocol	total energy consumption/cycle [mJoule]	Life time with a 3V/180mAh CR2032 lithium cell [days]
current RTF	0,467	48
enhanced RTF	0,307	73
current TTF	0,192	117
enhanced TTF	0,192	117
802.15.4	1,247	18
Reference	0,011	2045

Results when draining a lithium battery cell (CR2032, 3V/180mAh) with a tag executing the different protocols in the case when a reader is present is shown in Figure 7. The two enhanced modes show good results, with a maximum life time of over 300 days when 50 tags are in the vicinity of the reader. In the same situation, use of the 802.15.4 (bottom curve) results in less than 40 days of life time. Of course the reference protocol shows the best results because there is no need to spend any energy listening for a beacon signal from a reader.

Figure 6. Total energy consumption when executing different protocols and a reader is present.

Figure 7. Life time when executing different protocols and there is an available reader.

VII. CONCLUSIONS

Through simulations, Free2move's protocol for Active RFID and the enhanced protocol built on Free2move's and its different modes have been compared to 802.15.4 and to a fictive reference protocol. The simulations show that, for delay and throughput, it is possible to almost achieve an "optimal" (reference protocol) protocol based on a well defined usage of a radio channel. To minimize the total energy consumption of a tag, adoption to the special requirements of applications has to be used. To this end, a flexible protocol that can be re-configured on the fly is preferable. The enhanced protocol, with its Reader Transmits First-mode (RTF) and Tag Transmits First-mode (TTF), accompanied by an acknowledge message that includes configuration information for the tag, is thus suitable for a wide range of applications.

The contention based channel access supported by the IEEE 802.15.4 standard has been studied to see how well it is suited to be used for Active RFID applications. The throughput is good, but the overall energy consumption for IEEE802.15.4 in Active RFID applications indicates that it might not be the best suited protocol. The current Free2move protocol has lower energy consumption, and the enhanced protocol shows even lower energy consumption and thus longer life time for the tag battery. The good throughput for 802.15.4 is explained by the carrier sense that improves collision avoidance as well as by the short acknowledge packet from the reader, which lets the radio channel be better utilized by the tags. The enhanced protocol includes information in the acknowledge packet to set the tag to deep-sleep state, and the tag will thus occupy the radio channel less. With a deep-sleep period set to ten cycles, energy consumption will in the best case be 90% lower for RTF and 86% lower for TTF, when there is an available reader. When there is no available reader there is nothing to gain for enhanced TTF but the enhanced RTF shows 34% lower energy consumption.

The general conclusions of this paper are, first of all, that a protocol for Active RFID should use the principle of the enhanced protocol with its RTF- and TTF-modes for lower energy consumption. Second, this protocol should also include the carrier sense method used in 802.15.4 to achieve higher throughput and shorter payload packet delay. Lowering the energy consumption in the case when no RFID-reader is available is an interesting research challenge. Ideally a tag should never have to wake up and search for the reader but should stay in deep-sleep mode to lower the energy consumption.

Future work should consider new low power listening mechanisms, for example like in X-MAC [19].

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