THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

ENERGY EFFICIENT PROTOCOLS
FOR
ACTIVE RFID

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ABSTRACT

Radio frequency identification (RFID) systems come in different flavours; passive, active, semi-passive, or semi-active. Those different types of RFID are supported by different, internationally accepted protocol standards as well as by several accepted proprietary protocols. Even though the diversity is large between the flavours and between the standards, the RFID technology has evolved to be a mature technology, which is ready to be used in a large variety of applications. This thesis explores active RFID technology and how to develop and apply data communication protocols that are energy efficient and which comply with the different application constraints.

The use of RFID technology is growing rapidly, and today mostly “passive” RFID systems are used because no onboard energy source is needed on the transponder (tag). However, the use of “active” RFID-tags with onboard power sources adds a range of opportunities not possible with passive tags. Besides that Active RFID offers increased working distance between the interrogator (RFID-reader) and tags, the onboard power source also enables the tags to do sensor measurements, calculations and storage even when no RFID-reader is in the vicinity of the tags.

To obtain energy efficiency in an Active RFID system the communication protocol to be used should be carefully designed. This thesis describes how energy consumption can be calculated, to be used in protocol definition, and how evaluation of protocols in this respect can be made. The performance of such a new protocol, in terms of energy efficiency, aggregated throughput, delay, and number of collisions in the radio channel 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). Simulations show that, by acknowledging the payload and using deep sleep mode on the tag, the lifetime of a tag is increased.

For all types of protocols using a radio channel, when arbitrating information, it is obvious that the utilization of that channel is maximized when no collisions occur. To avoid and minimize collisions in the media it is possible to intercept channel interference by using carrier sense technology. The knowledge that the channel is occupied should result in a back-off and a later retry, instead of persistently listening to the channel which would require constant energy consumption. We study the effect on tag energy cost and packet delay incurred by some typical back-off algorithms (constant, linear, and exponential) used in a contention based CSMA/CA (Carrier Sense Multiple Access/ Collision Avoidance) protocol for Active RFID communication. The study shows that, by selecting the proper back-off algorithm coefficients (based on the number of tags and the application constraints), i.e., the initial contention window size and back-off interval coefficient, the tag energy consumption and read-out delays can be significantly lowered. The initial communication between reader and tag, on a control channel, establishes those important protocol parameters in the tag so that it tries to deliver its information according to the current application scenario in an energy efficient way. The decision making involved in calculating the protocol parameters is conducted in the local RFID-reader for highest efficiency. This can be done by using local statistics or based on knowledge provided by the logistic backbone databases.

As the CMOS circuit technology evolves, new possibilities arise for mass production of low price and long life active tags. The use of wake-up radio technology makes it possible for active tags to react on an RFID-reader at any time, in contrast to tags with cyclic wake-up behaviour. The two main drawbacks with an additional wake-up circuit in a tag are the added die area and the added energy consumption. Within this project the solution is a complete wake-up radio transceiver consisting of only one hi-frequency very low power, and small area oscillator. To support this tag topology we propose and investigate a novel reader-tag communication protocol, the frequency binary tree protocol.

Keywords: RFID, Active RFID, protocol, energy efficient, power consumption, back-off, wake-up radio, throughput, delay, RFID-system

SAMMANFATTNING

Radiofrekvensidentifierings (RFID) system finns i flera varianter; passiva, aktiva, semiaktiva eller semipassiva. Dessa olika varianter av RFID stöds av olika internationellt accepterade kommunikationsprotokoll och accepterade proprietära protokoll. Även om skillnaden är stor mellan de olika varianterna av RFID-system och mellan olika protokoll så har RFID-teknologin utvecklats till att bli en mogen teknologi som kan användas för en stor mängd olika applikationer. Denna avhandling studerar och visar hur man kan utveckla kommunikationsprotokoll för aktiv RFID som är energieffektiva och medger stöd för en mängd olika applikationer trots sina olikheter.

Användningen av RFID-teknologin ökar snabbt och idag används mest passiva RFID-system då transpondrarna inte behöver någon egen energikälla. Aktiva RFID-transpondrar med egen energikälla ger en rad möjligheter som inte är möjliga med passiva transpondrar. Aktiv RFID bidrar till utökat arbetsavstånd mellan läsare och transponder. Energikällan i en aktiv transponder gör det också möjligt att använda givare, göra beräkningar och lagra data även då det inte finns en läsare i närheten.

För att uppnå energieffektivitet i ett aktivt RFID-system måste kommunikationsprotokollet konstrueras med omsorg. Denna avhandling beskriver hur energikonsumtionen kan beräknas för att användas vid protokolldefinition och hur det då är möjligt att utvärdera ett protokoll. Prestanda för ett sådant nytt protokoll, ur energieffektivitetsynvinkel, antal lästa transpondrar per sekund, fördröjning innan en transponder blir läst, och antal kollisioner i luftgränssnittet, utvärderas och jämförs med existerande kommersiella protokoll för aktiv RFID samt med IEEE-standarden 802.15.4 (som används i Zigbee’s mediumaccesskontroll-lager). Simuleringsresultat visar att, genom att bekräfta att datapaketen från transpondern nått fram till läsaren och då sätta transpondern i sovläge, kan transponderbatteriets livslängd ökas.

För alla typer av protokoll som använder en radiokanal vid informationsutbyte åstadkoms bästa utnyttjandet av denna då kollisioner kan undvikas. För att förhindra eller minska risken för kollisioner är det möjligt att lyssna på kanalen (”carrier sense”) innan den utnyttjas. Vetskapen om att kanalen är upptagen medför att transpondern avvaktar i sovläge en stund (”back-off”), istället för att lyssna kontinuerligt i väntan på att kanalen skall bli fri och då förbruka energi i onödan. Vi har studerat energiförbrukningen och ID-utläsningsfördröjningen för en transponder då olika ”back-off”-algoritmer använts (konstant, linjär och exponentiell) för ett CSMA/CA (Carrier Sense Multiple Access / Collision Avoidance) baserat protokoll. Studien visar att, genom att välja lämpligt initialt back-off fönster och algoritmkoefficient (baserat på antalet taggar och applikationens art), kan energiförbrukningen och utläsningsfördröjningen minskas avsevärt. Vid den initiala kommunikationen mellan läsare och transponder förmedlar läsaren de viktiga protokollparametrarna till transpondrarna beroende på applikationsscenariot så att transpondrarna arbetar energieffektivt. Protokollparametrarna kan tas fram av RFID-läsaren och kan vara baserade på statistik från tidigare läsningar eller information från databaser som är knutna till RFID-systemet.

Utvecklingen av CMOS-teknologin ger nya möjligheter för massproduktion av aktiva transpondrar till ett lågt pris. Användning av ”wake-up”-radio teknik gör det möjligt för en RFID-läsare att väcka ”sovande” transpondrar i motsats till transpondrar som cykliskt vaknar och lyssnar efter en RFID-läsare. De två huvudsakliga nackdelarna med en wake-up-radio är den extra chipytan för att åstadkomma denna samt den extra energiåtgången för att driva densamma. Inom detta projekt har vi hittat en lösning där vi använder en wake-up-radio transceiver (sändare-mottagare) som endast består av en högfrekvent CMOS-oscillator med liten chipyta och låg effektförbrukning. Som stöd för denna transponder-arkitektur föreslår och utvärderar vi ett nytt läsare-transponder kommunikationsprotokoll. Detta protokoll bygger på en metod som använder ett frekvens-binär-träd för att extrahera en transponders identitet.

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B. Nilsson, L. Bengtsson, U. Bilstrup, P-A. Wiberg, and B. Svensson, "**Towards an Energy-Efficient Protocol for Active RFID**", *Proceedings of the IEEE Symposium on Industrial Embedded Systems*, IES 2006, Antibes Juan-les-Pins, France, October 18-20, 2006

Paper B

B. Nilsson, L. Bengtsson, B. Svensson, and P-A. Wiberg, "**Protocols for Active RFID - the Energy Consumption Aspect**", *SIES'2007 - IEEE Second International Symposium on Industrial Embedded Systems*, Lisbon, Portugal, July 4-6, 2007

Paper C

B. Nilsson, L. Bengtsson, P-A. Wiberg, and B. Svensson, "**The Effect of Introducing Carrier Sense in an Active RFID Protocol**", *Technical Report IDE-0766*, School of Information Science, Computer and Electrical Engineering (IDE), Halmstad University, Sweden, 2007

Paper D

B. Nilsson, L. Bengtsson, and B. Svensson, "**An Application Dependent Medium Access Protocol for Active RFID Using Dynamic Tuning of the Back-off Algorithm**", *IEEE International Conference on RFID 2009*, Orlando, FL, USA, April 27-28, 2009

Paper E

B. Nilsson, L. Bengtsson, B. Svensson, U. Bilstrup, and P-A. Wiberg, “**An Active Backscatter Wake-up and Tag Identification Extraction Protocol for Low Cost and Low Power Active RFID**”, *IEEE International Conference on RFID-Technology and Applications 2010*, Guangzhou, China, June 17-19, 2010

Paper F

E. Nilsson, B. Nilsson, L. Bengtsson, and B. Svensson,”**A Low Power-Long Range Active RFID-system Consisting of Active Backscatter Transponders**”, *IEEE International Conference on RFID-Technology and Applications 2010*, Guangzhou, China, June 17-19, 2010

Paper G

B. Nilsson, L. Bengtsson, and B. Svensson,”**A Snoozing Frequency Binary Tree Protocol**”, *Technical Report IDE1010*, School of Information Science, Computer and Electrical Engineering (IDE), Halmstad University, Sweden, 2010

Submitted to The Third International EURASIP workshop on RFID Technology, La Manga del Mar Menor, Cartagena, Spain, 6-7 September, 2010

OTHER PUBLICATIONS

B. Nilsson, L. Bengtsson, and B. Svensson,”**An Application and Energy Aware Active RFID Protocol**”, Intended to be submitted to *EURASIP Journal on Wireless Communications and Networking*, April 2010

B. Nilsson, L. Bengtsson, P-A. Wiberg, and B. Svensson, "**Selecting Back-off Algorithm in Active RFID CSMA/CA Based Medium-access Protocols**", *SIES'2008 - IEEE Third International Symposium on Industrial Embedded Systems,* Montpellier, France, June 11-13, 2008

B. Nilsson, "RFID, den smygande lilla jätten", *Hallands Affärer*, November 2007

AWARDS

Awarded first prize (shared) at the “Competition for RFID Nordic Scholarship”, *Scandinavian RFID Expo and conference*, 21-24 October, 2008

Competition contribution “Towards Energy Efficient Protocols for Active RFID”, *Licentiate thesis*

The prize is initiated by RFID NORDIC an interest organization with over 50 members including companies and universities. Among them are the Royal institute of technology - KTH Information and Communications Technology, MOTOROLA Enterprise Mobility, POSTEN Logistik AB, SIS Swedish Standards Institute, SIEMENS AB, INTERMEC, and Swedbank.

1 INTRODUCTION

Radio frequency identification technology, RFID, has a long past, a fast evolving present, and a grand future. This technology, which sharp minds have refined and evolved for more than half a century, is used to obtain order and control of "things".

RFID technology has been growing rapidly in usage the last decade. RFID is used to remotely and wirelessly identify a device named *transponder* (or ***tag***) by using an *interrogator* (or ***reader***) and is depicted in Figure 1. The tag has a unique identity (could be used as an electronic product code, EPC) used to identify the object it is attached to.

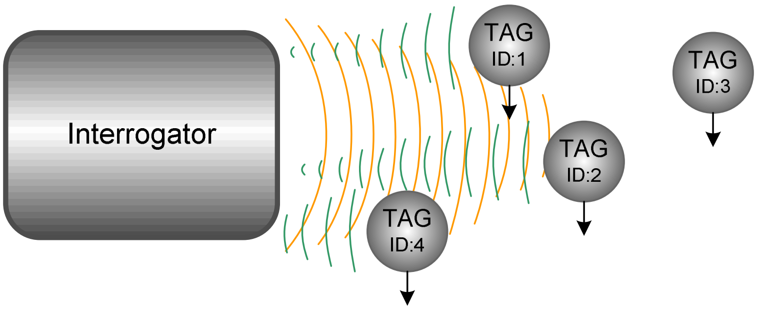

Figure 1. An RFID-system where tags are passing a reader. The tags in range of the interrogator identify themselves by transmitting their unique IDs.

RFID was first used during the Second World War in long range systems on aircrafts where you needed to decide whether an approaching object was friend or foe (IFF, Identification, Friend or Foe systems) [1]. It took four decades, until the 1980s, before RFID became commercially used [2] in, e.g., personnel access, animal tracking, and road tolls. Figure 2 shows an early estimation of the growth in the global RFID market. The fastest growing market from 2003 onwards is in the supply chain management.

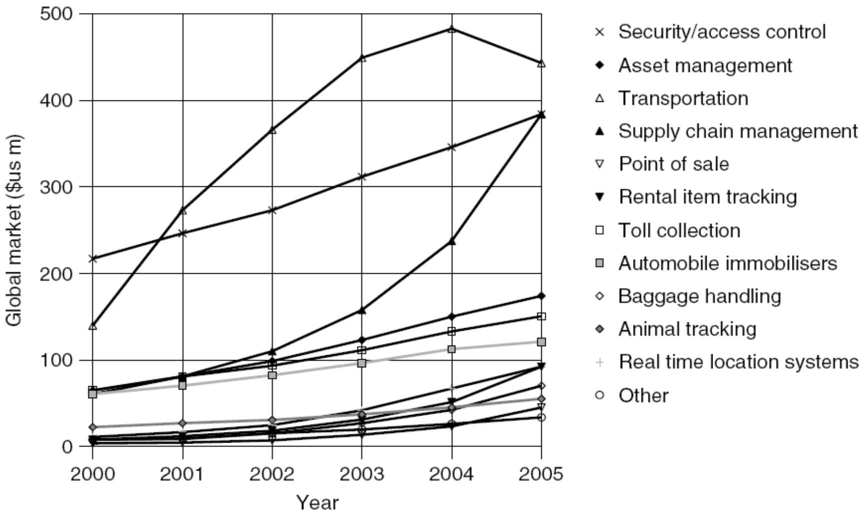

Figure 2. The estimated growth of the global market for RFID systems between 2000 and 2005 in million $US, classified by application. Figure 2 source: RFID Handbook, K. Finkenzeller, 2003, Copyright John Wiley & Sons Limited. Reproduced with permission.

One of the most common applications where RFID-systems are used today is indeed the logistics chain depicted in Figure 3, where RFID tags replace barcodes [3].

The producer marks the product with a tag and can use it for local tracing at the factory. While the goods are under transportation the tag is traced with a global tracing system. At the wholesaler's warehouse it is used for automated inventory and when distributed to the retailer used for proof of delivery. The retailer uses the RFID-system for inventory to know when to order new merchandises. Further on in the chain the tag can be used for information about product status. For instance, a sensor could be included on the tag, telling what temperature stress the product has been under, so the consumer can decide if it is worthwhile buying the product (for instance, vegetables that are sensitive to temperature changes).

The number of applications where to use RFID is only limited by the imagination of the inventors of the applications and of the engineers that construct the systems.

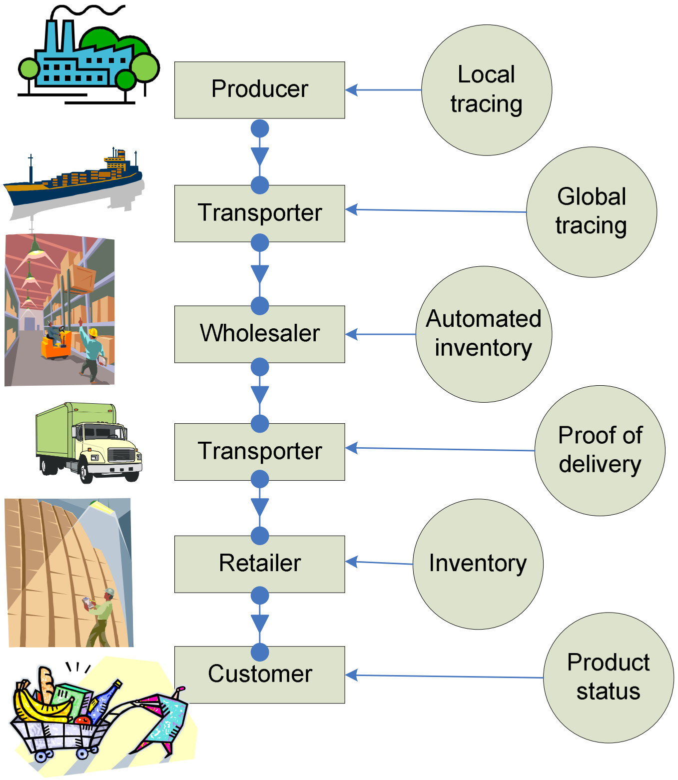

Figure 3. Logistics chain supervision

Other areas where RFID is developing and growing is in security applications [4], e.g. entrance surveillance or payment authentication. A very "hot" area at the moment for research and product development is applications using Real Time Location System (RTLS). Those systems must make use of both RFID-systems as well as middleware and backbone structures.

To provide for the usage of RFID-systems worldwide there must be an agreement on a standard (or maybe a few standards). Today there exist a variety of standards and proprietary (privately owned and controlled) standards which often cannot communicate with each other and do not share the same properties (e.g. information format/storage and physical communication) [5].

In my thesis work I have investigated the possibilities of defining one common RFID protocol that grasps over a large set of applications without deteriorating the performance regarding tag life-time (energy consumption aspect). The requirements on this single RFID protocol should be extracted from the full variety of applications that can be identified within e.g. Figure 3. One, or possibly a few, standardized protocols worldwide would enable producers of RFID technology to cooperate, which would lower the prices, and in turn expand the market even further.

1.1 APPLICATION SCENARIOS

Automation in logistics has driven the development of RFID in the past few years. Scenarios for RFID might for instance be in the logistics 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 (Figure 4) and passes an RFID-reader. In this realm, RFID could also be used for automatic inventory of the stock in a warehouse (Figure 5), where the reading delay is not critical but where there is a huge amount of tagged goods to identify.

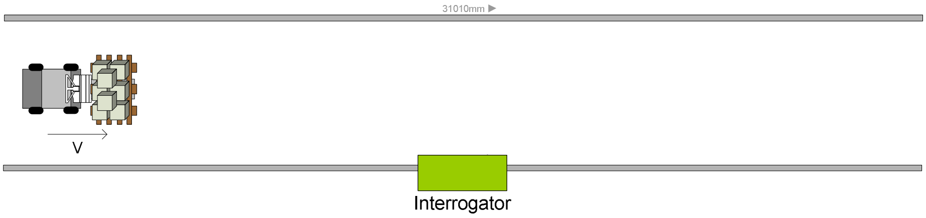

Figure 4. The fork lifter scenario where the goods on the pallet have to deliver their identity fast when the fork lifter passes the RFID-reader.

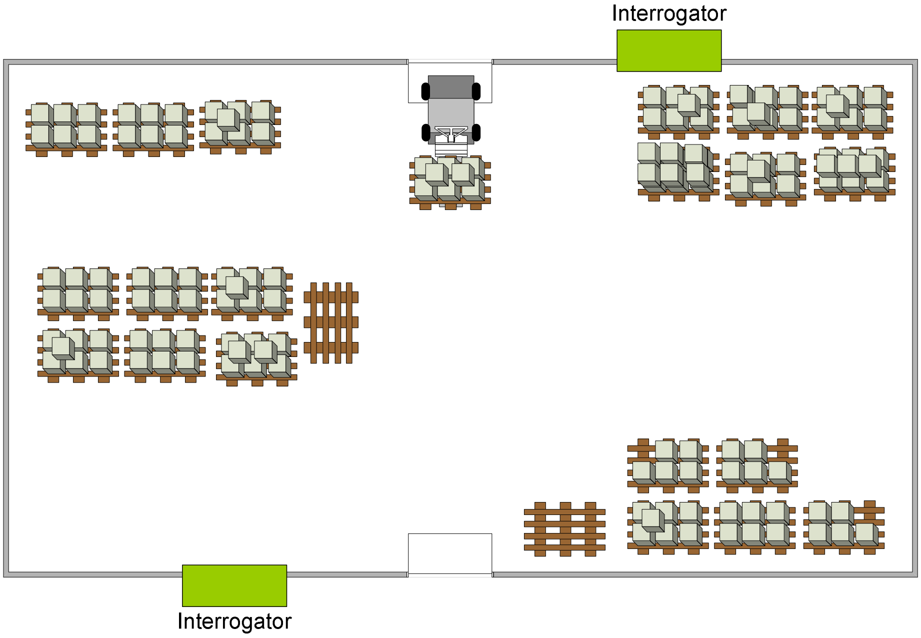

Figure 5. The warehouse scenario where a large amount of goods are stored and its status has to be continuously updated in the inventory database.

In some applications the physical constraints (e.g. radiated power from the reader) of the RFID-system set the limit of functionality (e.g. limits the reading range). The RFID-reader in the fork lifter scenario (assuming there is a narrow passage) needs only a small amount of energy, due to the short distance, but needs fast readings due to the high vehicle velocity. For the warehouse scenario, with long distances, the reader needs high level of radiated energy or many RFID-readers (yielding the known drawback with the "multi-reader problem", where readers interfere with each other, which deteriorates readability), but this scenario has no hard real time restrictions.

To pave the way for one protocol to fit different applications, some questions are at place. For instance is it possible to satisfy all the mentioned requirements in one protocol and only use one technology?

Could the protocol support both passive and active RFID, long and short reading range, and possibly few and vast numbers of tags?

1.2 SECURITY IN RFID

Many of the applications in which RFID is used need security in different degrees. For instance access control for buildings, where cloning a tag on a unique passage card (or maybe a passport) is not acceptable. Another area, where proof of origin is essential, is medicine, to be able to disable counterfeit medicaments.

Security issues when using RFID technology are going to accelerate as the usage of the technology increases. Much work has been done in this area [6]. Still, there is no single solution to solve the different existing types of issues and there might never be one either.

The security issues are correlated to the communication protocols (typically the number of communication rounds increases). In this thesis we focus and specifically address the energy efficiency for active RFID protocols correlated to the application demands.

2 PASSIVE AND ACTIVE RFID

Mostly "passive" RFID technology ("P-RFID") (meaning that the tag has no power source of its own [7]) has been in focus, but recently also "active" RFID ("A-RFID") (where the tag has an onboard battery) [8, 9] has gained more interest [10, 11]. By using an onboard power source for the tag (instead of power radiated from the reader), a wide range of applications are enabled that passive RFID cannot support. 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. 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 used in the tags. The drawback is that the use of active circuits limits the life-time of active tags compared to passive ones. The wireless RF-link is the part that consumes most of the tag power. Therefore, to achieve longer battery life-time for an active tag, an energy efficient protocol for Active RFID must be used.

2.1 PROS AND CONS, ACTIVE OR PASSIVE

The most common RFID technology today is the P-RFID. The tags have no energy source of their own but instead they are powered by the reader's magnetic or electromagnetic field which is converted to electrical power by the tags [12, 13, 14]. Although this enables low-cost tags the main drawbacks are: 1) the limited working distance between reader and tag (up to a few meters); 2) the high transmitted reader energy required; and 3) the fact that sensor readings and calculations are not possible when no reader is in the vicinity to power the tags.

In A-RFID the working distance can be much longer (up to a few hundred meters). A-RFID tags, having their own power sources, can use higher transmit power and make use of receivers with higher sensitivity due to active amplification. Another benefit is that sensor measurements, calculations, and storage are possible even when no reader is in the vicinity of the tags. In P-RFID systems the reader has to continuously radiate high energy to power the tags, while that is not the case in active systems. Also, in the case where a large area has to be covered, many readers have to be deployed in passive systems while only a few in active ones.

The possible rate of detecting tags is dependent on, for instance, the combination of signal propagation loss due to range and output power from the reader. For scenarios which need fast detection of tags this implies dense readings close to the reader in P-RFID (the reader powers the tags only from a short distance). A-RFID systems can spread the readings in the time domain and in distance from the reader (the tags have their own power sources, yielding longer working distance and higher transmission speeds) and therefore offer a higher throughput of tag readings.

3 RFID PROTOCOLS

To achieve good performance when transferring information between RFID reader and tags we use a communication protocol. The diversity among communication protocols is a problem for the RFID users if they want to merge with business partners using a different RFID system.

3.1 TODAY'S STANDARDS AND PROTOCOLS

Standardization of RFID has been going on for some years and has led to different standards used for different applications and in different parts of the world [15]. There are also many proprietary "standards".

Figure 6 depicts the taxonomy of RFID technologies. It is possible to classify RFID as P-RFID, S-RFID (semi passive/semi active), and A-RFID.

The "semi" means that the tags are partly battery powered (in most cases the battery is assisting a more complex processor core) to boost functionality compared to P-RFID. For the different classes there exists a variety of different standards, defacto standards, and proprietary "standards".

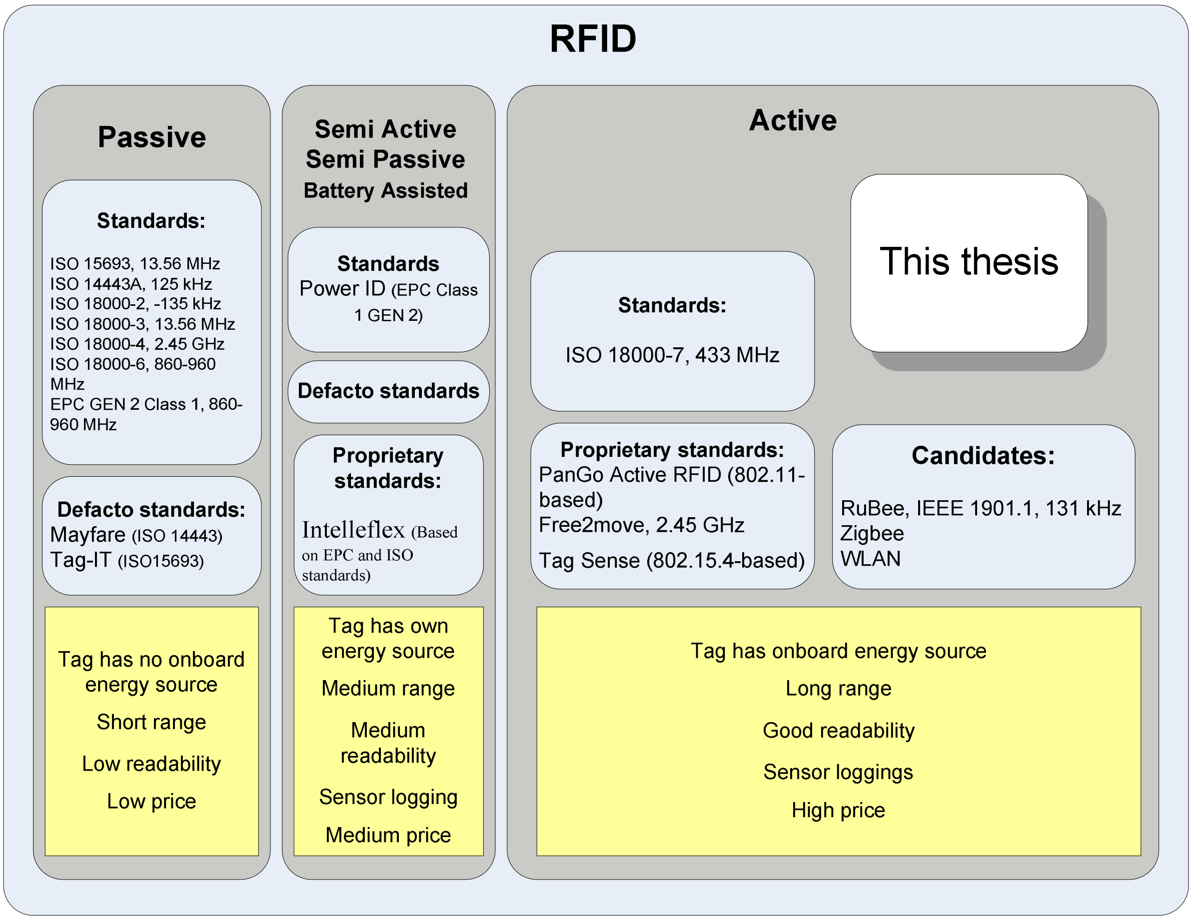

Figure 6. The taxonomy of RFID technologies (Passive RFID, semi-active/semi-passive RFID, and Active RFID) and their properties. This thesis work, in the Active RFID domain, focuses on data communication energy efficiency, aiming at maximizing tag battery lifetime.

The figure also shows some of the properties (readability = probability of success when reading the tag ID) and what the limitations are for the systems applied to the different groups. Notably, when walking rightwards in the figure, we get higher performance at the cost of a higher price for the tag device. A lot of standardization work has been done for P-RFID, for instance the EPCglobal Class 1 Gen 2 (ISO/IEC 18000-6 Type C) air interface [16] (work of AUTO-ID Center, originally initiated by Massachusetts Institute of Technology). For A-RFID mostly proprietary "standards" exist. However, some existing standards used, for example, in WLAN and sensor networks (e.g. Zigbee) are currently being used for A-RFID despite their disadvantages regarding tag price and battery life-time.

3.2 STANDARDS FOR A-RFID

The standard ISO 18000-7 [17], in the A-RFID group of Figure 6, defines the air interface for a device acting as an active tag in the 433 MHz 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. An implementation [18] of ISO 18000-7 shows good readability but rather poor performance for dense tag applications, due to the arbitration technique used and the long time to retrieve tag information.

There exist many proprietary protocols that are specialized for different tasks in automation and logistics, but there exists no protocol that tries to accommodate solutions for a large variety of applications.

3.3 A-RFID TECHNOLOGIES

In this thesis we report on the use of the Zigbee MAC layer (Medium Access Protocol), IEEE 802.15.4, for A-RFID [19, 20].

An A-RFID system using IEEE 802.15.4 (described as "Zigbee-ready") has been constructed by the company Tagsense [21]. Applications supported by their ZT-10 tag is asset tracking and monitoring, monitoring of prisoners, tracking livestock, remote sensing and monitoring, secure locks, sensor data logging, and tagging of pallets, vehicles, people, animals, and buildings.

Unfortunately Zigbee shows some disadvantages, with long connecting delays when used for A-RFID. Link establishment for Zigbee, 15-30 ms as shown by Lönn et al. [22], might be considered short for a wireless network but for an A-RFID-system it is a too long delay when retrieving payloads in a dense tag environment (best case using Zigbee would be reading 66 tags per second, but for A-RFID typically it needs to be several hundred per second).

Bridgelall [23] has proposed an architecture for a hybrid back-scatter RFID tag that uses a Bluetooth enabled P-RFID tag. A passive ISO standard tag can activate the Bluetooth radio (also on the tag) to add communication bandwidth.

State of practice systems like AeroScouts's Wi-Fi based active tags enable the wireless network infrastructure to accurately track the location of valuable assets or people [24]. This system has the drawback of a high price, high energy consumption, and low throughput (due to long connection time).

Some research has been conducted on protocols for wireless local area networks (WLAN) to decrease energy consumption. X-MAC, presented by Buettner et al. [25], is a result of this work, presenting a short MAC protocol for duty-cycled wireless sensor networks. X-MAC has a shortened preamble approach which significantly reduces energy usage.

None of the above mentioned A-RFID-systems aim at applications with dense tag readings.

3.4 CYCLIC AWAKENING SYSTEMS AND WAKE-UP RADIO SYSTEMS

The activation of transponders in an A-RFID system is possible in at least two ways. One way is by letting the tag continuously or cyclically listen for an RFID reader, and when found one, transmit its ID (“Reader Transmit First” method) or just send the tag ID (“Tag Transmit First” method) when it cyclically awakens.

Another method is by using a wake-up radio circuit that activates the tag when there is an RFID reader, transmitting beacons, in the vicinity of the tag. This can be an active wake-up circuit which consumes low power and offers a long awakening distance, e.g. as shown by Nilsson et al. [26], or it can be a passive circuit, not consuming any energy, but offering a more moderate awakening distance. The different methods are depicted in Figure 7.

Various solutions for wake-up radios have been published [27, 28, 29, 30, 31]. They suffer from difficulties like low receiving sensitivity resulting in short reading range, awakening due to false signals, need of cyclic synchronizing, and need for a more complex transceiver.

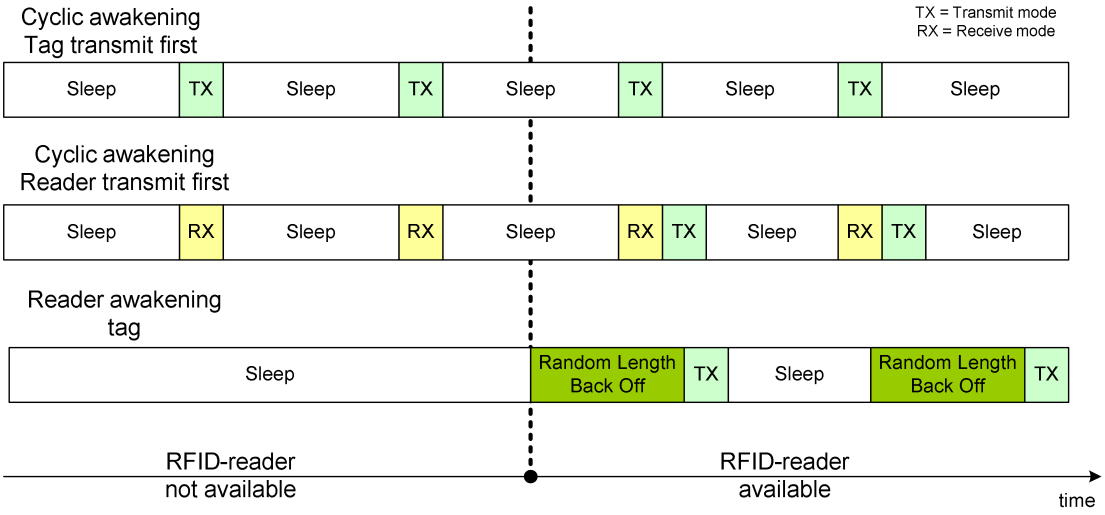

Figure 7. Some of the possible ways for a tag to deliver its ID. Either it cyclically awakens, the two top scenarios in the figure, or it uses a wake-up transceiver that awakens the tag when there is a reader at hand, the bottom scenario. In the latter scenario, due to the possibly vast number of tags awakening at the same time, tags start by doing a random length back-off in order not to collide when trying to identify themselves.

4 MOTIVATION

The use of Radio Frequency Identification systems is growing rapidly. Today, mostly the P-RFID systems are used because no onboard energy source is needed on the transponders. However, A-RFID technology, with onboard power sources in the transponders, gives a range of opportunities not possible with passive systems. Besides offering longer operating range between RFID-reader and tag in an active system than in a passive one, the tag power source used in active tags also enables sensor measurements, more complex calculations and storage of information even when no RFID-reader is in the vicinity of the tags.

To profit from all the benefits that A-RFID is paving the way for, the transponders' operating lifetime and manufacturing cost must be addressed as important issues to solve. New architectural solutions for small-area, low-power baseband processing as well as for small-area, low-power RF-blocks will be required to cut the active-transponders unit cost. To obtain energy efficiency in an A-RFID system the communication protocol to be used should be carefully designed with energy efficiency in mind. This thesis is focused on the communication protocol issues.

4.1 PROBLEM FORMULATION

To better understand the general issues of energy efficiency of active RFID protocols, the research reported in this thesis has focused on the following problems:

- How energy effective are some of the active RFID communication protocols of today?
- How does the lifetime and power consumption of active RFID transponders relate to the radio communication protocols?
- How can the energy efficiency for a transponder using an active RFID protocol be calculated?
- How does the use of carrier sense influence the energy efficiency of an active RFID transponder?
- If carrier sense is to be used, then what type of back-off algorithm should be used?
- Which are the controlling parameters for the back-off algorithm, and how are they related to the applications?
- If we use enabling wake-up radio technology, how should the communication protocol be designed?
- How could an RFID system for wake-up based transponders look like?

5 GOAL, APPROACH AND CONTRIBUTIONS

The goal of this thesis is to investigate and find solutions on how the radio communication protocol can be tailored for active RFID regarding enhancing the transponder battery lifetime.

5.1 APPROACH

To reach this goal by addressing the above problems, the following approach has been used:

- Investigation of existing communication protocols already used, or potentially to be used for active RFID.
- Development of mathematical equations on how to calculate energy efficiency, throughput, and read-out latency.
- Evaluation of carrier sense functionality when used in a radio channel.
- Evaluation of various back-off methods used in a MAC protocol for active RFID.
- Design of a cyclic wake-up protocol reducing power consumption by using carrier sense and a variable back-off algorithm tailored to the actual application at hand.
- Survey of methods for deciding the number of transponders in range of an active RFID reader.
- Design and performance evaluation of a wake-up radio based active RFID communication protocol.
- Proposal of a wake-up radio based active RFID-system.

5.2 CONTRIBUTIONS

The research has resulted in the following specific contributions, all published in the papers that are appended to the thesis:

- Evaluation of existing commercially available active RFID protocols, and an active RFID protocol based on IEEE 802.15.4. Reported in **Paper A**.

- Suggestion on how power consumption can be calculated for Active RFID protocols and be used in protocol definition when calculating energy efficiency, read-out delay and throughput. Described in **Paper B**.

- Evaluation of the use of carrier sense functionality in active RFID protocols. Evaluated in **Paper C**.

- Method to select proper back-off algorithm, algorithm coefficients, and initial contention window size in a contention based CSMA/CA active RFID protocol. Described in **Paper D**.

- Definition and investigation of a frequency signaling binary tree protocol to support an active RFID system with low complexity, low power, and low price active transponders. Described in **Paper E**.

- Definition of an active RFID system based on a wake-up RFID transponder. Shown in **Paper F**.

- Enhancement and following evaluation of the frequency binary tree protocol. Described in **Paper G**.

6 SUMMARY OF APPENDED PAPERS

This section gives an overview and a short summary of each of the appended Papers, A-G, in this thesis.

6.1 PAPER A

B. Nilsson, L. Bengtsson, P-A. Wiberg, U. Bilstrup, and B. Svensson, "**Towards an Energy Efficient Protocol for Active RFID**", *IEEE Symposium on Industrial Embedded Systems*, Antibes, France, 18-20 October, 2006

To obtain energy efficiency in an Active RFID system, a protocol should be designed that is optimized with energy in mind. This paper describes initial work on how to define and evaluate such a protocol. The protocol's performance in terms of energy efficiency, aggregated throughput, delay, and number of air collisions is evaluated and compared to that of the medium-access layer in 802.15.4 Zigbee, and also to a commercially available protocol from the company Free2move AB.

In this paper we compare different protocols and their energy cost per successfully delivered payload bit from a tag to a reader with a fictive *Reference* protocol ("optimal", meaning that the tag does not need any energy to wake up when there is a reader in the vicinity). This is the most energy efficient protocol shown in Figure 8. The *Tag Transmit First* (TTF), and *Reader Transmit First* (RTF) protocol modes are not as efficient as the one based on *IEEE 802.15.4*. The main reason for this is that 802.15.4 uses carrier sense, avoiding collisions, whereas TTF and RTF do not.

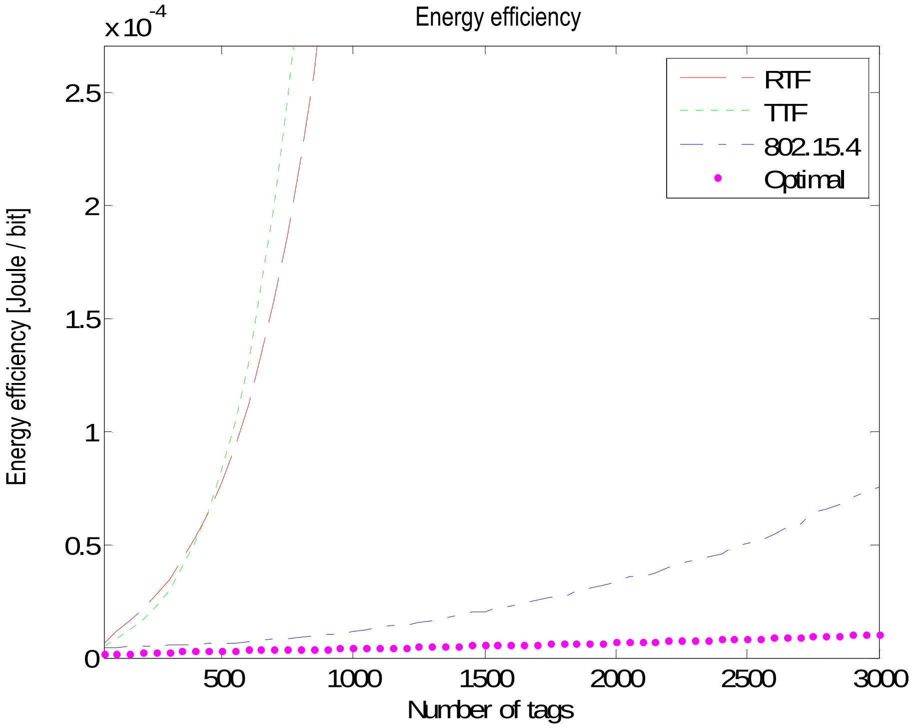

Figure 8. Energy cost per successfully delivered payload data bit.

6.2 PAPER B

B. Nilsson, L. Bengtsson, P-A. Wiberg, and B. Svensson, "**Protocols for Active RFID — The Energy Consumption Aspect**", *IEEE Second Symposium on Industrial Embedded Systems*, Lisbon, Portugal, 4-7 July, 2007

This paper describes how energy consumption can be calculated, to be used in protocol definition, and how evaluation of protocols 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 one based on IEEE standard 802.15.4 (used e.g. in the Zigbee medium-access layer).

By applying the simulation results on actual power consumption, the lifetime of a tag can be calculated. Calculation methods are presented and used in this paper for showing the lifetime of a tag running the different protocols. Results from these calculations are shown in Figure 9.

The enhanced protocol includes information in the acknowledge packet to put the tag in deep-sleep state, and the tag will thus occupy the radio channel less. With a deep-sleep period set to ten cycles, the 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 power consumption.

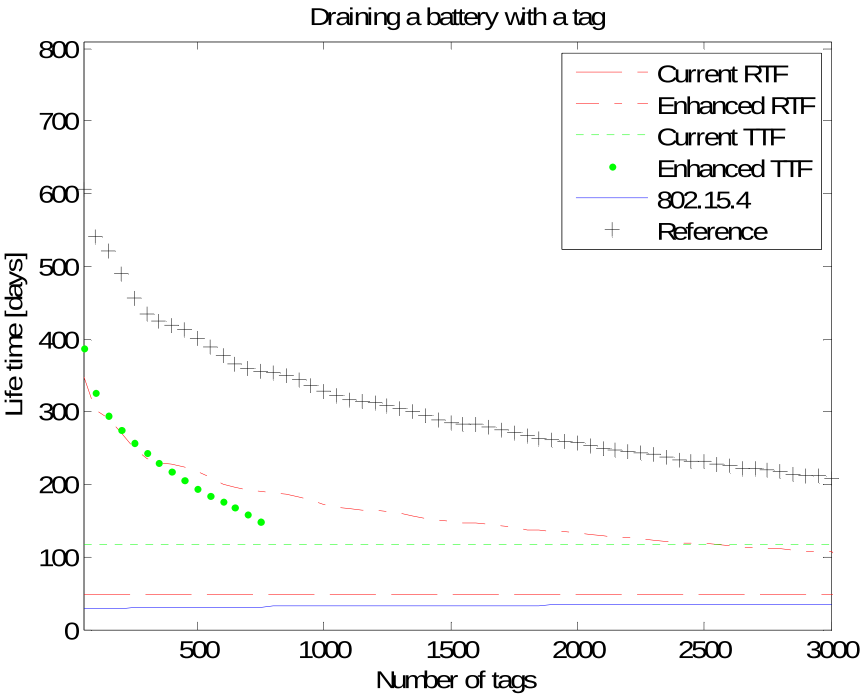

Figure 9. Total life-time for a tag executing different protocols assuming there is an available reader in the vicinity. The "Enhanced" RTF and TTF are modified versions of RTF and TTF, where a "deep-sleep" ability has been added saving power. 802.15.4 shows short battery lifetime due mainly to the long listening time needed to identify the beacon signal.

6.3 PAPER C

B. Nilsson, L. Bengtsson, P-A. Wiberg, and B. Svensson, "**The Effect of Introducing Carrier Sense in an Active RFID Protocol**", *Technical Report IDE0766*, Halmstad University, CERES, September 2007

This paper shows that the Carrier Sense (CS) facility in IEEE 802.15.4 [32], when used for A-RFID, increases the energy efficiency. The CS is used to avoid air collisions in the radio channel. Using the carrier sense functionality has an advantage as long as the energy consumption for this action is held low. Figures 10, 11 and 12 show simulation results for comparisons between using and not using CS in the same protocol. For instance, in Figure 10 the CS protocol has 2.3 times higher throughput when there are 400 tags and 5 times higher for 1000 tags.

Every tag wakes up during a cycle (the cycle time is set to 1 second in this case), at a time which has a uniform random distribution. The CS protocol, which is the top graph in Figure 10, shows highest throughput and heads towards maximum channel utilization (which theoretically is 556 tags/second). The throughput would of course decrease if propagation delays increase (and are of great magnitude) as shown by Rom and Sidi [33].

In this simulation the propagation delay is set to zero but for real cases it is less than 200 ns and is a small fractional part of the CS (128 µs), resulting in a very low impact on the propagation delay. Figure 11 shows the delay (average message delay when all tags have delivered at least one payload each).

The CS protocol shows good results even with a dense tag population (3000 tags). The graph for the protocol not using the CS raises rather quickly, resulting in a long delay already when only a small amount of tags are in the proximity of the reader. Repeating the CS until the channel becomes free consumes less energy than having to retransmit the payload if collision occurs. The expected lifetime, presented in Figure 12, reveals the much lowered energy consumption when using CS.

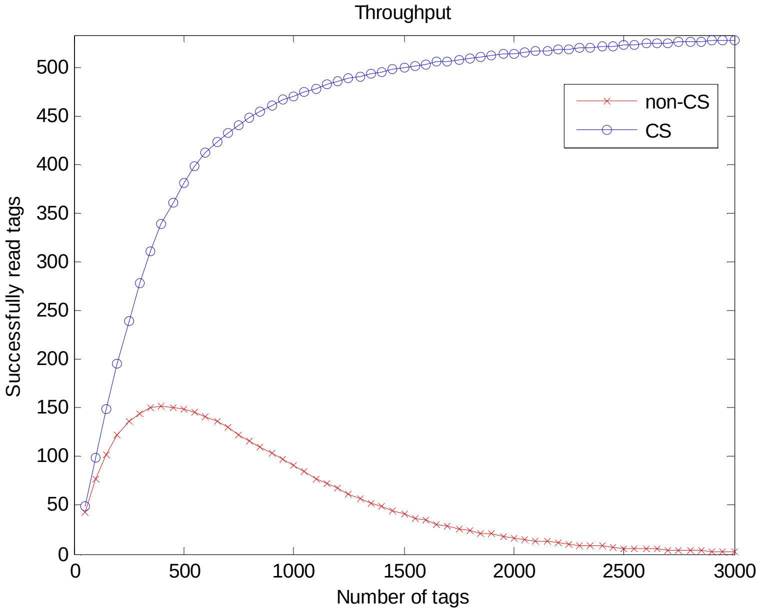

Figure 10. Throughput, number of read tags per second.

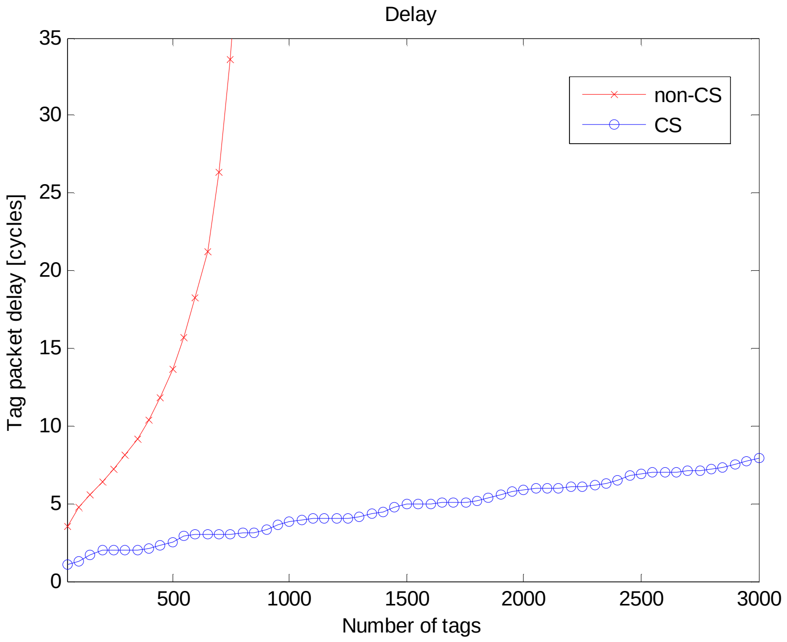

Figure 11. Delay, average time to read all available tags (the cycle time is set to 1 second).

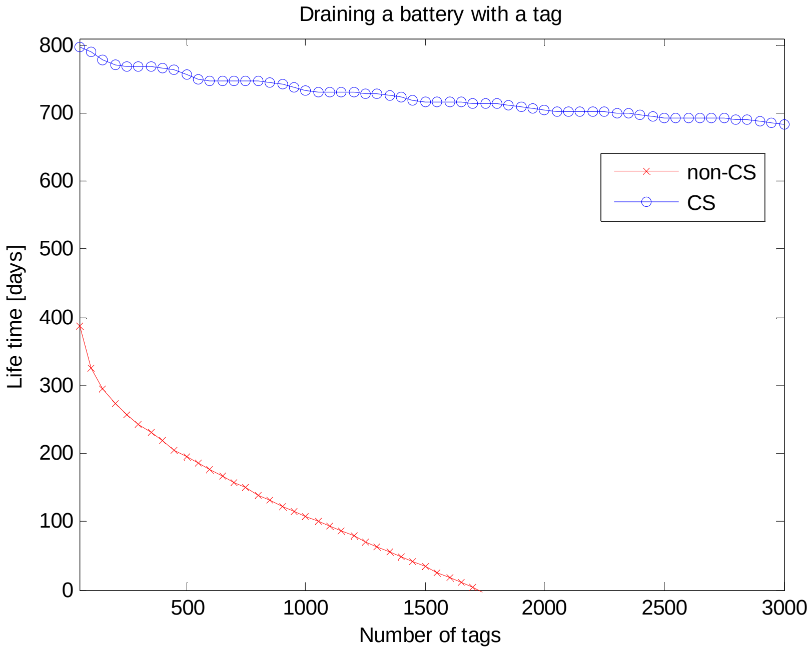

Figure 12. Lifetime (days) a CR2032 (150 mAh) lithium cell will last. The non-CS curve is extrapolated above 800 tags.

6.4 PAPER D

B. Nilsson, L. Bengtsson, and B. Svensson, "**An Application Dependent Medium Access Protocol for Active RFID Using Dynamic Tuning of the Back-off Algorithm**", *IEEE International Conference on RFID 2009*, Orlando, FL, USA, April 27-28, 2009

Paper D is a study of the effect on tag power consumption and packet delay incurred by some typical back-off algorithms (constant, linear, and exponential) used in a contention based CSMA/CA (Carrier Sense Multiple Access/ Collision Avoidance) protocol for Active RFID communication. The study shows that, by properly selecting the back-off algorithm coefficients (based on the number of tags), i.e. the initial contention window size (*ICW*) and back-off interval coefficient, the tag energy consumption and read-out delays can be significantly reduced.

Figure 13 shows, for the case with constant back-off time, the power consumption, (average power consumption for a tag to deliver its payload), the delay (average delay time for a tag to deliver its payload), and the energy delay product, *EDP*, as a function of the number of tags and the back-off time coefficient, C. The *EDP* diagram includes a black-dotted white line which shows the minimum *EDP* when evaluating a specific amount of tags and choosing, for the constant algorithm, the best suited coefficient C and the most appropriate initial contention window (not shown, extracted from simulations).

The technical report [34] contains such diagrams for all back-off algorithms. The information retrieved from the diagrams can be used to fit the algorithms to an RFID application. Paper D shows, by combining the algorithm with the best suited length of the initial contention window and the best fitted coefficient, that all the algorithms accomplish low power consumption. Some extended energy savings were achieved when applying a modulus operation to the coefficient in the algorithms.

To obtain a general measure of how the algorithms behave under different loads, an average *EDP* value has been calculated. The calculated average *EDP* shows the minimum energy delay product that is possible to accomplish by varying the algorithm coefficient and the *ICW*. The average *EDP* values are shown in Table 1. The exponential algorithm without modulus shows much worse performance compared to the others. However, by using modulus five on the back-off counter, the average *EDP* can be lowered considerably, 88% in the exponential algorithm. In the linear algorithm, the use of modulus gives an improvement of only 10%. The conclusion is that, regarding average *EDP*, the constant, the linear, and the exponential (with modulus) algorithms are equally good, assuming that the *ICW* and the coefficients have been properly chosen.

In Paper D we also discuss the need to be able to predict the number of tags at hand at the RFID-reader to support a variety of application scenarios with different requirements on energy consumption and read-out delays. For the type of A-RFID scenarios considered, where the number of tags is varied as well as how fast they pass a reader, simulation results show the importance of, based on the number of tags, selecting the correct length of the Initial Contention Window and the algorithm coefficient. For some of the scenarios the delay is of prime concern, and in some the number of tags. In all cases the power consumption is important. The proposed method of using a dynamic back-off scheme results in lowered average tag power consumption (increased tag battery life time). A non-dynamic scheme would need to utilize worst-case parameters, yielding the highest power consumption values in all scenarios. To estimate the number of available tags at an RFID reader, we propose to use existing data bases, e.g. in the logistics chain.

Table 1. Average *EDP* for different algorithms.

Algorithm	Average *EDP* [mJoule Second]
Constant	0.61
Linear	0.67
Linear modulus	0.60
Exponential	5.00
Exponential modulus	0.60

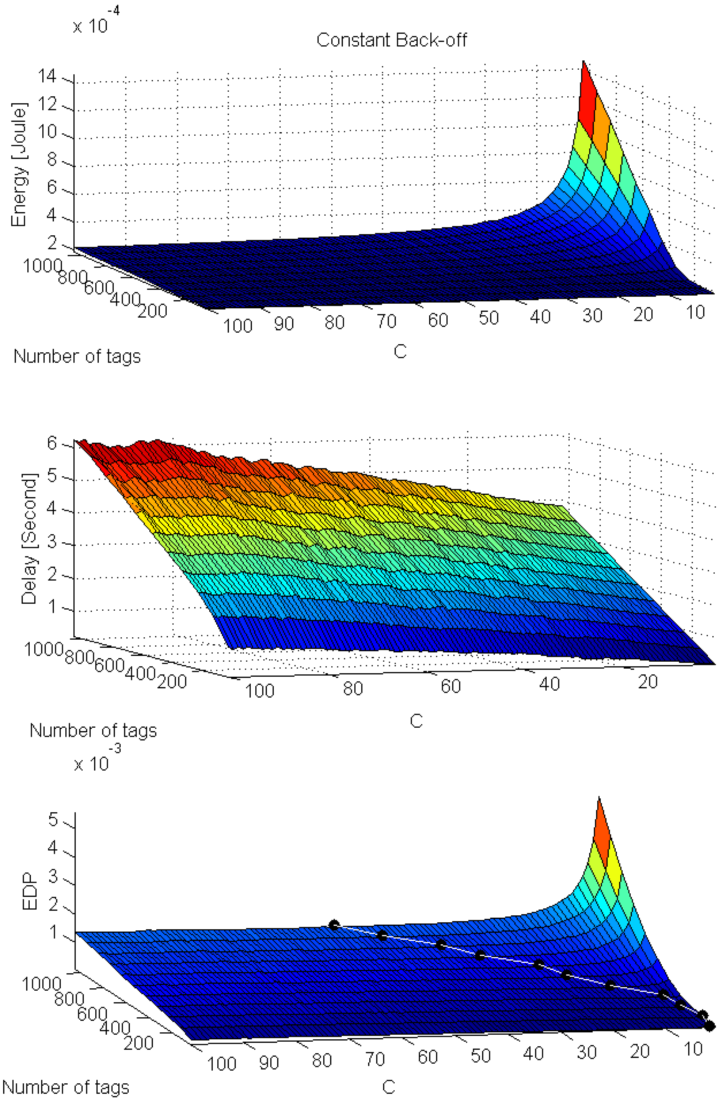

Figure 13. Constant back-off time power consumption (top), Delay (middle), and Energy-Delay Product (bottom) as a function of the coefficient C and the number of tags.

6.5 PAPER E

B. Nilsson, L. Bengtsson, B. Svensson, U. Bilstrup, and P-A. Wiberg, "**An Active Backscatter Wake-up and Tag Identification Extraction Protocol for Low Cost and Low Power Active RFID**" ", *IEEE International Conference on RFID-Technology and Applications 2010*, Guangzhou, China, June 17-19, 2010

In this paper we present a Radio Frequency IDentification communication protocol used to wake up and extract the ID of every tag (or a subset thereof) within reach of a reader in an active backscatter RFID system. We also study the effect on tag energy cost and read-out delay incurred when using the protocol, which is based on a frequency binary tree method, see Figure 14.

The frequency binary tree protocol can be used for addressing single tags or for reading out all tags within reach from the reader. Calculations and simulations, when using the 2.45 GHz ISM band, show that the protocol enables a throughput of 1570 tags per second and that the average delay when reading a tag ID in a population of 1000 tags is 319 ms. Using this protocol, the estimated lifetime for a tag powered by a low-cost 7x7 square centimeter printed battery is almost three years, in scenarios when the tag's ID is read out once every 60 seconds.

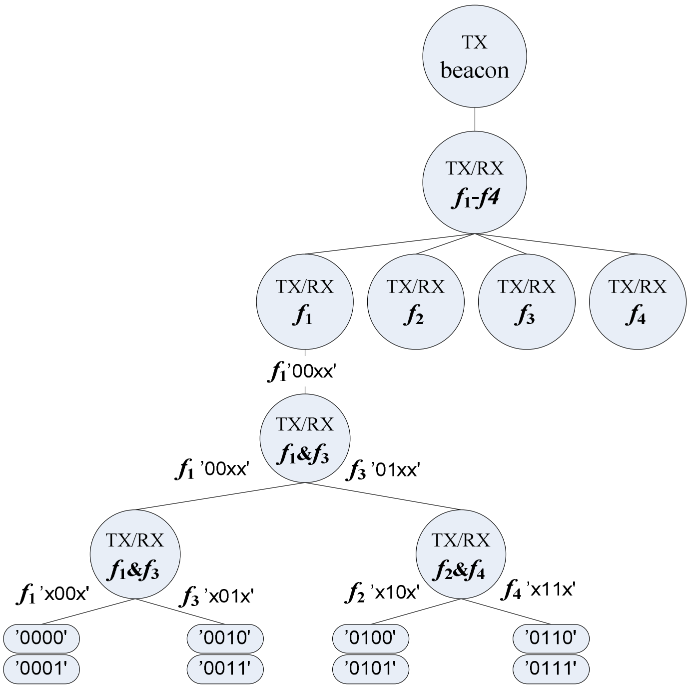

Figure 14. Structure of the frequency binary tree. The reader initiates a reading with the beacon (top level). Then it checks what frequencies f_1-f_4 tags are responding at (2nd level). In the 3rd level, it randomly chooses one of those and transmits on that frequency, in this case on f_1. In the following steps it randomly chooses a frequency to continue with until it reaches the end and has read the ID(s).

6.6 PAPER F

E. Nilsson, B. Nilsson, L. Bengtsson, and B. Svensson,”**A Low Power-Long Range Active RFID-system Consisting of Active Backscatter Transponders**”, *IEEE International Conference on RFID-Technology and Applications 2010*, Guangzhou, China, June 17-19, 2010

In this paper we present a novel active radio frequency identification system consisting of transponders with low complexity, low power consumption, and long system reading range. The transponder’s low complexity and small circuit integration area indicate that the production cost is comparable to the one of a passive tag. The hardware keystone is the transponder’s radio wake-up transceiver, see Figure 15, which is a single oscillator with very low power consumption. The communication protocol, based on a frequency signaling binary tree, contributes to the low complexity of the tag architecture.

Wake-up radio technology, such as the one described and used in this paper, gives a number of benefits for RFID applications, most importantly that a tag is reachable by the RFID reader at any time and does not need any advanced synchronized wake-up algorithms. Like in conventional radio front-ends, important issues in wake-up radios are power consumption, method of synchronization, and total silicon area of the mixed signal die. Reducing tag complexity infers a corresponding increase in reader complexity.

In a low-frequency system (20 MHz) that has been implemented and tested, the principle of operation has been proven. Transferring the reader design to the 2.45 GHz ISM band includes using standard off-the-shelf technology, with no added complexity or changes in functionality, see Figure 16. The low complexity and power consumption of the described backscatter radio transceiver enables low-cost tags with long reading range, two-way communication (tag - reader), and sensor logging.

Synchronization between reader and tags is done using a frequency binary tree communication protocol that can be used for addressing single tags or for reading out all tags within reach from the reader. With this active RFID system more than 1500 tags can be read per second. The average delay when reading a tag ID in a population of 1000 tags is 319 ms. The reading range of the active RFID system is 50 meters. The estimated life time for a tag, in this active RFID system, powered by a low-cost 7x7 square centimeter printed battery, is almost three years, in a scenario where the tag’s ID is read out as often as 60 times per hour.

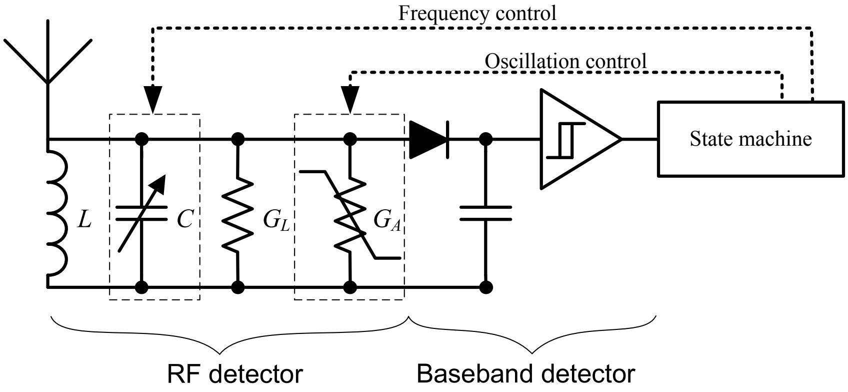

Figure 15. The principle of the tag radio architecture.

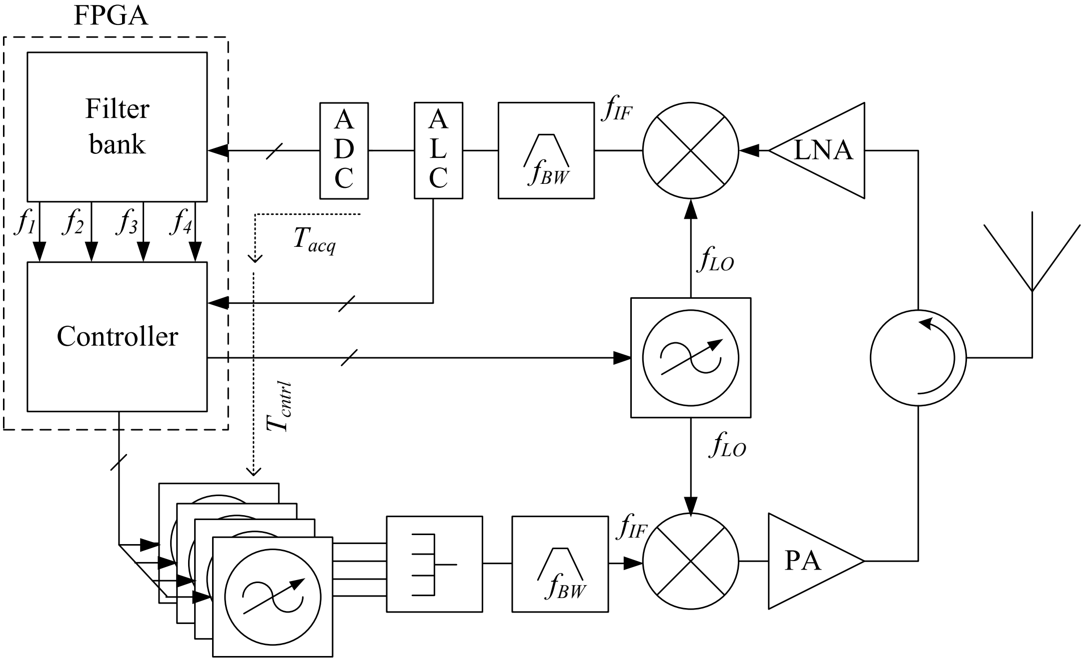

Figure 16. Reader hardware implementation block diagram.

6.7 PAPER G

B. Nilsson, L. Bengtsson, and B. Svensson,"**A Snoozing Frequency Binary Tree Protocol**", *Technical Report IDE1010*, School of Information Science, Computer and Electrical Engineering (IDE), Halmstad University, Sweden, 2010

Submitted to The Third International EURASIP workshop on RFID Technology, La Manga del Mar Menor, Cartagena, Spain, 6-7 September, 2010

The frequency binary tree protocol described in Paper F can be enhanced (lowering the power consumption) by using a framed and slotted MAC method including a simple back-off strategy to minimize the number of tag activations during read-out of the tag ID.

The enhanced protocol is used with the wake-up transceiver tag described in Paper F. The protocol with the enhancement works as follows, see Figure 17. After the tag has received its first beacon signal from the RFID reader, which awakens the tag, it randomly chooses a slot in the pre-defined frame and sets the beacon counter to the corresponding random number. When the tag is awakened by a beacon signal it counts down the beacon counter and snoozes until next beacon. If the beacon counter reaches zero, the tag tries to deliver its ID. This procedure is continued until the tag successfully has delivered its tag ID; subsequently it enters deep-sleep mode and does not participate in further ID extraction for a pre-determined time.

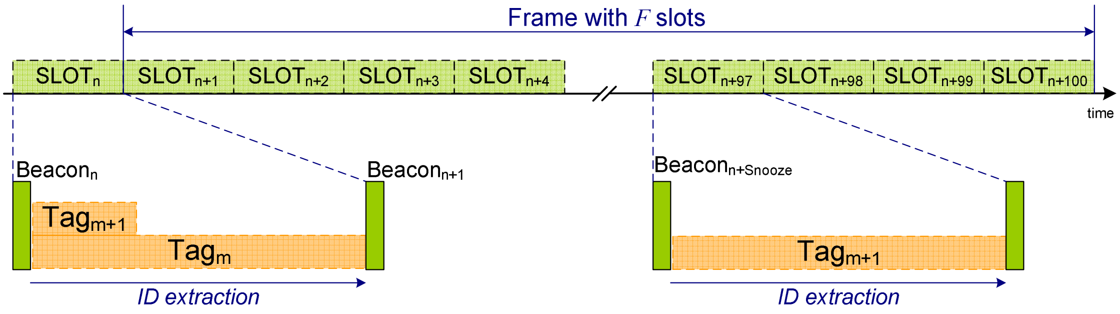

Figure 17. After Beacon$_n$, Tag$_{m+1}$ contends with Tag$_m$ to deliver its ID. Tag$_{m+1}$ is not selected by the reader and randomly chooses a new slot in a new frame with F slots (F=100) to wake up in. It snoozes until the chosen slot arrives, and once again it tries to deliver its ID and succeeds.

Simulation results of the two different protocols are shown in Figures 18 & 19. The frame used in the simulation contains 100 slots. With the enhanced protocol and a population of 1000 tags the average read-out delay of a tag ID is increased by 0.9%. The average number of tag activations is decreased by 2.5 times compared to the original protocol. Further studies will be conducted on this protocol and how to optimize the selection of the frame length according to the tag population and the specific application scenario at hand. This protocol has one disadvantage compared to the original protocol, and that is the ability to address one single tag by using the "frequency trail" described in Paper E. A solution is to vary the length of the beacon signal. Different distinct lengths of the beacon signal could add the possibility to give the tags different commands. The selected number of slots in the frame should also be chosen appropriately, according to the tag population as shown in [33, 35].

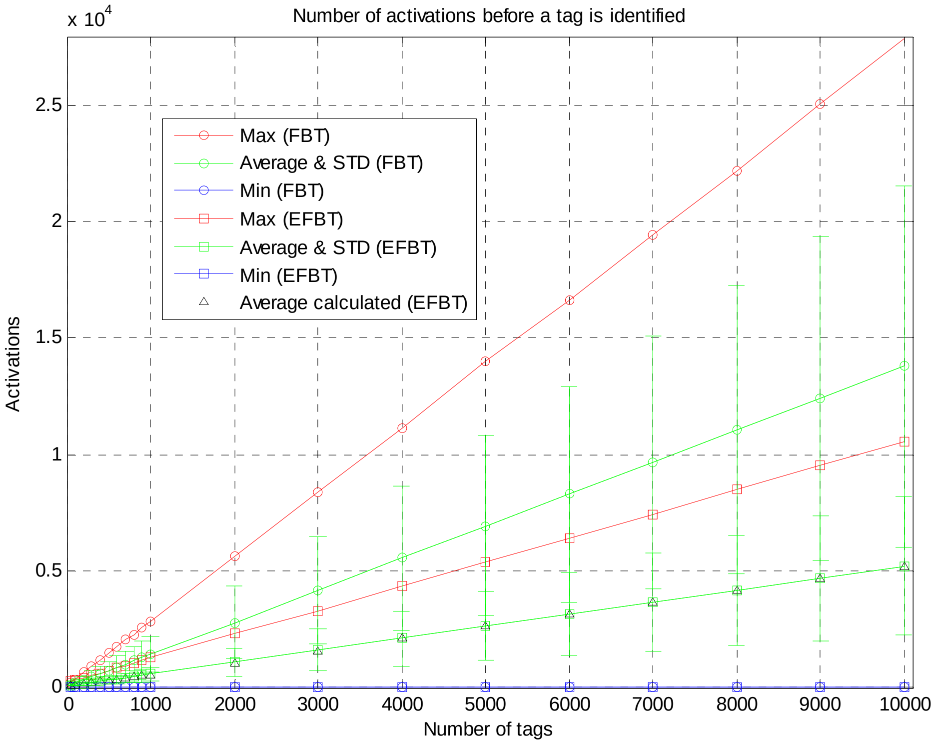

Figure 18. When using the enhanced protocol (EFBT) the average number of activations with a population of 1000 tags is decreased by 2.5 times. The maximum number of activations is decreased by 2.2 times. The calculated average for the enhanced protocol co-inside with the simulated average.

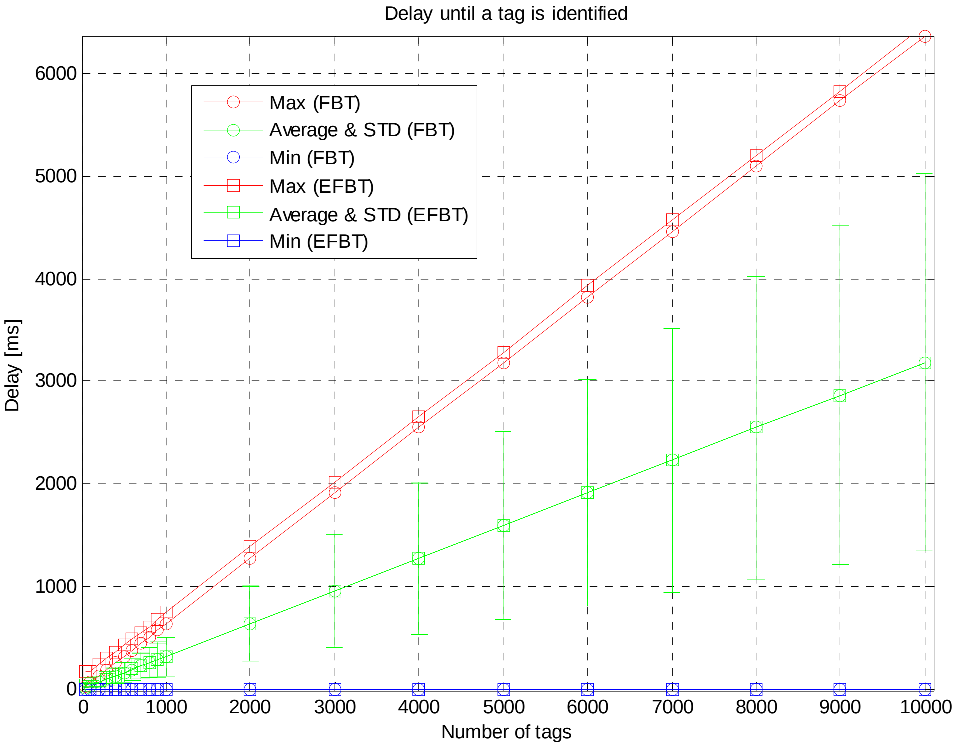

Figure 19. The delay of the both protocols is displayed showing e.g. when there are 1000 tags available to the reader that the enhanced protocol has an increased max delay of 17%, but the average delay with the same number of tags is only increased by 0.9%.

7 RELATED RESEARCH WORK

Protocols for A-RFID is an important but surprisingly unexplored research area. There are many companies developing systems used for A-RFID, but no agreement exists of a worldwide standard that fits a large variety of applications. Scientific publications that report investigations on how to reduce power consumption for an A-RFID tag seem to be scarce. Much research work has been published on wireless sensor networks but this is not easily adaptable to A-RFID.

Some research work done on improving protocols for P-RFID to lower the power consumption of the readers (passive readers in most cases consume a whole lot more power compared to active ones), and surprisingly also the passive tags. Parts of this work are applicable to A-RFID. An energy-aware tag anti-collision protocol is presented by Namboodiri, and Gao [36]. The results show that, when combining a binary tree search protocol with frame-slotted ALHOA, tag collisions can be minimized and thereby it is possible to do energy savings.

A multichannel slotted-ALOHA protocol for active RFID is presented by Yoon et al. [37]. They show that by increasing the number of used radio channels the collisions among the tags decrease, thereby reducing the read out delay. Avoiding collisions reduces the overall power consumption due to the fact that the rate of retransmission also decreases.

An analysis of power consumption and read out delay in existing passive RFID protocols applied to active RFID is conducted by Su et al. [38]. They decrease the total power consumption of a tag by reducing both the total identification time and the total active time by changing the used frame size.

Research done by Bhanage et al. [39] to enable a power efficient reading protocol for A-RFID shows interesting results. Their idea is to reduce information sent in the network and also to reduce the energy used to detect collisions by enabling smart sequencing in real time. The Relay MAC protocol proposed yields better throughput and energy conservation than a conventional “select-and-read” protocol (a binary search protocol used in for instance P-RFID). The disadvantage of the Relay MAC protocol is that the reader coordinates the reading sequence, which means that, when a load with new ID-tagged goods arrives at a reading spot, the reading sequence has to be re-initialized.

An anti-collision algorithm for A-RFID is proposed by Li et al. [40] enabling increased energy efficiency. The RFID-system uses two channels, one for data and one for control. Every tag starts by doing an exponential back-off and then starts to send. The reduced power consumption is explained to be due to the tag power-down-mode during the back-off. The authors report on simulations with up to 20 tags, which is a rather small tag population. They claim a life-time of five years when the battery capacity is 950 mAh and 100 readings are made per day. Nothing is mentioned about how many tags that were used in the A-RFID-system when achieving the five years of life-time.

An interesting (relating to our described “reference” protocol, in Paper A, that simulates this feature) way of reducing power is described by Chen et al. [41]. Instead of the tag waking up periodically, a sensor based wake up is used. Their experiments show that, with a sensor-enhanced active RFID system, the battery lasts twice as long in comparison to a system without any embedded sensors.

With focus on awakening a tag by using low energy, Hall et al. [42] have constructed a “turn on circuit” in standard CMOS technology based on a Schottky barrier diode for Active RFID labels. Calculations of the usable “turn on” range (using a favorably oriented antenna with an antenna gain of 6 dB and an operating frequency of 915 MHz, and output power of 1 W (as is allowed under FCC regulations for the UHF ISM band)) will give a theoretical operating range of 117 meter.

Shweta et al. [43] have developed a CSMA-based [33] MAC protocol to avoid collisions in a dense RFID network. Results from evaluations show that it has superior performance to a naive and to a randomized protocol with regard to readability (probability that many readers read the same tag when the tag is in vicinity to all readers at the same time) and time per tag read.

A stochastic anti-collision algorithm, the DFSA algorithm (Dynamic Framed Slotted ALOHA) is investigated by Leian et al. [44]. In a slotted ALOHA-based anti-collision RFID system it is shown that, when the number of slots is the same as the number of tags, maximum throughput is achieved. For estimation of the number of tags, two methods are presented and demonstrated.

8 CONCLUSIONS

This thesis work concludes that active RFID brings the RFID technology closer to a vast of applications not applicable by only using passive RFID, and one of the keys to succeed is the communication protocol.

The thesis is focused on the communication protocols for active RFID in an energy perspective. To lower the power consumption for transponders and increase the transponder battery lifetime in an active RFID system the communication protocols at hand is of great importance. In the extremes, it is shown in this thesis that it is possible to increase the lifetime of a transponder from 50 days to over 800 days by having energy in mind when developing the communication protocol. We also show that it is possible to not only control the power consumption but also control the read-out delay (time to extract the full transponder identity). This important protocol feature can be used when adapting the RFID-system to different application scenarios at hand. Different scenarios also imply different numbers of transponders available. We discuss different methods in how to know the transponder population, and propose to use the available databases in, for instance, the logistics chain.

There are two main types of active RFID-systems, cyclic awakening systems and wake-up radio systems. In the cyclic awakening systems, the transponder is awakened cyclically and tries to deliver its information, sometimes without knowing if there exists an RFID-reader. In the wake-up radio based system the RFID-reader awakens the transponders in reach so they can deliver their information. To serve those two different types of systems the protocols must be tailored separately because of the different nature of the hardware technology used.

For the cyclic awakening systems we have considered CSMA/CA (Carrier Sense Multiple Access / Collision Avoidance) protocols. For systems using a wake-up radio we have developed a novel frequency binary tree protocol. Simulation results show that there is an advantage of using the carrier sense technique for cyclic awakening systems to reduce collisions in the radio channel and thereby, both lower the power consumption of the transponder and shorten the read-out delay. We also show that it is important to choose the accurate back-off strategy and the accurate back-off parameters for the CSMA/CA based protocol to reduce the power consumption and read-out delay to meet the requirements of different application scenarios.

The wake-up radio based system considered in this thesis has been equipped with a novel frequency binary tree protocol. We show through simulations and calculations that it is possible to read more than 1500 transponders per second and that the average read-out delay is 319 ms in a population of 1000 transponders. We also estimate, when using a printed battery with the size of 7x7 square centimeters, the lifetime of a transponder to be more than three years if the transponder´s identification number is read every 60 seconds.

We also consider and evaluate a frequency binary tree protocol in combination with a framed and slotted medium access control method to achieve less activations of the transponder and in turn reduce the power consumption of the same. The study shows that the number of activations can be lowered with a factor of two, and still the average read-out delay will increase with less than one percent.

9 FUTURE WORK

The variety of applications in which RFID can be used is limited only by imagination. However, defining a protocol that is power and performance efficient over the entire imagination space seems to be a non-imaginable task. In order to use a protocol that can adapt to the application at hand we need information that characterizes the current circumstances and requirements.

9.1 PREDICTING THE NUMBER OF TAGS

One issue to address is how to predict the number of tags available to the RFID-reader. For applications where the number of tags is highly predictable, easy statistic calculations can be used, e.g. a normal distribution averaging (over time) window. Kheiri et al. [45] use a method where they, by reading tags during a period of time can estimate the total number of tags. The method used to model the number of tags is inter-arrival times for a renewal process.

A method suggested by Floerkemeier [35] which shows good performance compared to existing approaches predicts the tag population by using Bayesian broadcast strategies. The transmission control scheme is based on framed ALOHA and makes no restrictive assumption about the distribution of the number of tags close to the reader.

Applications in which the number of tags seems to be totally unpredictable are of course particularly challenging. One way to handle those cases, and possibly all cases, is to use information in databases, possibly several connected ones. The databases that typically already exist in the distribution chain contribute as a usable source of information for the RFID-readers. Figure 20 shows how a possible distribution flow could look like and where the readers could be placed. An RFID-reader that reads a tag can use the tag ID to get other specific information from a database. Useful information could be whether the specific tag that was read is in a batch of tags and, if so, how many tags were in that batch. In this way it is possible to know how to choose the protocol parameters to optimize the power consumption or the read-out delay. Naturally this depends on the middleware connecting readers together. A load balancing method proposed by Park et al. [46] that uses a connection pool for the middleware which enhances system flexibility and availability.

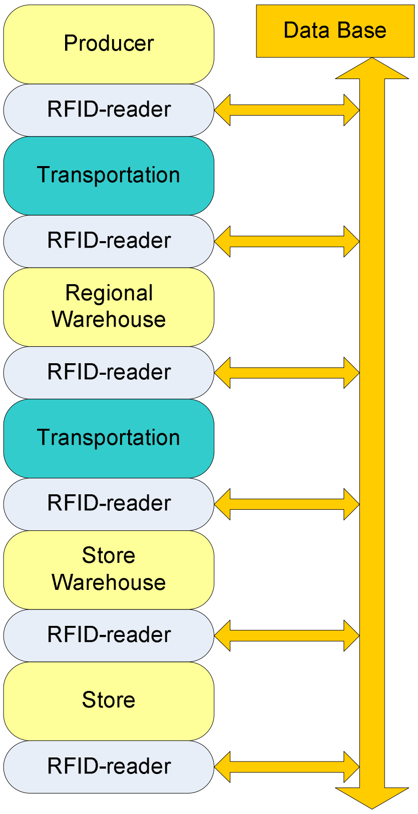

Figure 20. The database connected via the backbone, enabling continuous tracking of goods.

In many cases RFID is introduced in order to lower cost in the distribution chain and maintain visibility of goods during transportation or storage. This is done by using a backbone, connecting different databases used by the involved logistic companies. As an example, Yu et al. [47] propose, for mobile RFID tags, a protocol by which the reader discriminates newly arriving tags from the leaving tags. This reduces the number of readings done by the RFID-reader, and the database only has to update changes in the tag population, resulting in decreased tag read delay and higher tag read throughput.

Potdar et al. [48] propose to address the issue of non-read tags by comparing the actual weight of the tagged goods available at the reading spot with the expected when comparing to information in a database where the goods weight is stored. By doing this it is possible to know if any tags (actually any goods) were missed in the read process. This seems to be a good choice for the supermarket when customers themselves should attend to the payment of the articles at the exit.

The continued work regarding the back-off protocol will focus on how to automate the decision on how to choose the algorithm parameters to be optimized for a variety of application scenarios. The above discussion should be considered as an introduction to some of the issues for practical RFID scenarios and some of the solutions for the same.

9.2 AN ACTIVE RFID-SYSTEM DEMONSTRATOR

As described and discussed in Paper G, there are still enhancement margins for the binary tree communication protocol to achieve even lower power consumption and thereby increasing the tag battery life-time. Furthermore, mechanism for security in this type of protocol has to be studied and described to satisfy a variety of applications where this is absolutely needed.

Within the project of developing a novel active RFID system the present author has conducted research on communication protocols for the communication between RFID-readers and tags. Future work in the project is to develop a demonstrator system, using the 2.45 GHz Industrial, scientific and medical frequency band, and verify the research work done up till today. From the results on the demonstrator system, new and exciting research questions will come alive.

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