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DEVELOPMENT OF AN ULTRA-HIGH RADIO-FREQUENCY IDENTIFICATION SYSTEM

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ABSTRACT

Ultra-high radio-frequency identification (UHF RFID) systems outperform all other RFID technologies in terms of throughput and reading range. UHF RFID tags and readers will be deployed on unprecedented scales during the next few years. This could result in problems of inter-operability and large-scale interference from readers.

This thesis describes the systematic analysis of operational requirements and the systematic derivation of a set of design objectives and guidelines for a UHF RFID system and air protocol that differs from other UHF RFID systems in use today. In brief, this is a system where the reader transmits little or no data to the tags and is therefore low noise and narrow band. This makes this system (and specifically the protocol) one that can support a higher density of readers, and thus leads to an improved system throughput and effectiveness.

The principal challenge is to design and implement a tag protocol that addresses all of the requirements derived for the UHF RFID system. Thus, at the core of the system is the iP-X anti-collision protocol, a stochastic Aloha-like over-the-air communications protocol. The protocol is described and analysed in this work, both in terms of its throughput performance as an anti-collision protocol, and also in terms of its RF characteristics and benefits.

The major result of this work is the successful implementation of a series of tag chips that have been designed to implement the protocol. Both readers and tags are currently in production and are being successfully marketed and sold worldwide.

SAMEVATTING

Ultra-hoë radio frekwensie identifikasie (UHF RFID) stelsels presteer beter as alle ander RFID tegnologieë ten opsigte van leesafstand en deurvoer tempo. UHF RFID etikette en lesers sal in baie groot getalle in gebruik gestel word gedurende die volgende paar jaar. Dit kan lei tot aanpasbaarheidsprobleme en steurings tussen lesers.

Hierdie tesis beskryf die analise van die operasionele vereistes en die ontwikkeling van 'n stel ontwerpdoelwitte vir 'n RFID stelsel en meegaande lugprotokol wat verskil van ander RFID stelsels wat vandag in gebruik is, naamlik 'n RFID stelsel waarin die leser min of geen data na die etikette stuur nie. Die leser is dus nou-band en genereer min steurings. Die eindresultaat is dat hierdie stelsel en protokol 'n hoër digtheid van lesers toelaat, en dus lei tot groter rendement en deurvoertempo.

Die hoof uitdaging is om a RFID protokol te ontwerp wat aan al die behoeftes vir 'n RFID stelsel voldoen. Die hart van die stelsel is die iP-X kommunikaksie protokol tussen die leser en die etikette. Die protokol is 'n stogastiese protokol gebaseer op die Aloha protokol. Die protokol word beskryf en ge-analiseer, beide in terme van deurvoertempo asook in terme van die protokol se RF eienskappe en voordele.

Die hoof resultaat van hierdie werk is die suksesvolle ontwerp van 'n reeks geïntegreerde stroombane wat die protokol implementeer. Die bane is huidiglik saam met lesers in produksie en word wêreldwyd bemark.

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GLOSSARY

ACA	Australia Communications Authority.
Active tag	RFID transponder containing a battery or other power source.
AVI	Automatic Vehicle Identification.
BTG	British Technology Group.
CW	Continuous wave.
dB	Decibels. Ten times the log10 of the ration of two quantities.
dBi	dB gain relative to isotropic.
dBc	dB relative to carrier.
dBm	dB relative to 1 mW in 50 Ω.
dBd	dB gain relative to a dipole.
EAN	Electronic Article Numbering.
eirp	Effective isotropic radiated power.
EPC	Electronic Product Code.
ERC	European Radio Communication Committee.
ERP	Enterprise Resource Planning.
erp	Effective radiated power relative to a dipole.
ETSI	European Telecommunications Standards Institute.
EVI	Electronic Vehicle Identification.
FCC	Federal Communications Council.
GSM	Global System Mobile.
GTAG	Global tag.
GTIN	Global Trade Identification Number
HF	High Frequency – for RFID the band 7 MH– 13.56 MHz.
ICASA	Independent Communications Authority of South Africa.
ID	Identification code.
IP	Intellectual Property.
ISM	Industrial, Scientific, Medical.
ITS	Intelligent Transport Systems.

ISO	International Standards Organisation.
LF	Low Frequency – for RFID the band 125 kHz – 500 kHz.
LFSR	Linear Feedback Shift Register.
MIS	Management Information System.
Passive tag	RFID transponder containing no battery or other power source. Instead the transponder is powered by an energy beam transmitted by a reader.
RF	Radio Frequency. For RFID frequencies above 125 kHz.
RFID	Radio Frequency Identification.
RTF	Reader Talks First.
Rx	Receive.
SAL	Semi-active Label.
SAW	Surface Acoustic Wave.
SCM	Supply Chain Management.
SRD	Short range devices.
RCS	Radar Cross-section.
Tag	RFID transponder.
TEL	Tag Excitation Level.
TTF	Tag Talks First.
Tx	Transmit.
UHF	Ultra High Frequency – for RFID the band 860-930 MHz.

1. SCOPE

1.1. Definition of need: Automatic identification

A need exists for the automatic identification of goods in all spheres of industry. Specific applications include the tracking of goods through a supply chain, authentication of goods and transactions, stock taking and check-out, theft and fraud prevention, automatic identification of vehicles, people and animals, and more applications not listed here. For supply chains specifically, efficiency improvements can be achieved if the specific requirements as set out below, can be met.

1.2. System requirements for supply chain management

1. Automatic reading without manual intervention;
2. Long range identification (further than 2 m);
3. High speed reading (more than 100 objects identified per second);
4. Identification of objects moving at high speeds;
5. High system throughput rates. That is, it must be possible to operate a large number of identification stations in parallel at the same time;
6. Low cost (less than USD 0.05);
7. Large identification ID code space. Enough to uniquely identify every object in the total supply chain;

1.3. Technology solutions to the set requirements

Figure 1 below gives an overview of the automatic identification technologies that are currently available. A more detailed discussion of the various identification technologies can be found in Chapter 2.

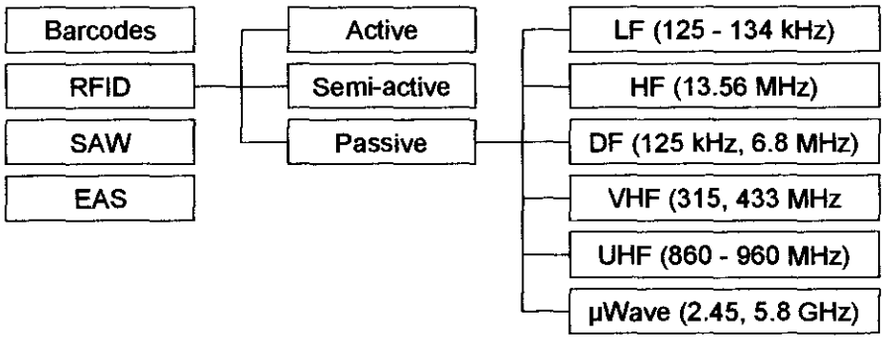

Figure 1: A taxonomy of automatic identification technologies

Currently ***bar codes*** are used for the bulk of the automatic identification requirements, especially in supply chains. Bar codes are extremely cheap but bar code reading has a number of disadvantages. The most important technology shortfalls are:

- Line of sight is required;
- Bar codes can easily be obscured by dirt or physical damage;
- Only fairly short reading ranges can be achieved (a few cm);
- Reading is slow (in the order of 1 per second);
- Data content is limited and cannot be changed;
- Reading must often be done manually.

When comparing the limitations of bar codes to the supply chain identification requirements, it is clear that a different identification technology is needed. Bar coding only meets one of the requirements, namely the cost factor.

Electronic Article Surveillance (EAS) systems are in reality only one-bit identification systems, and cannot meet the requirement of a large code space.

Surface Acoustic Wave (SAW) devices do not contain any active components and can potentially be manufactured at low cost. However, these devices suffer from a limited numbering range and are not field-programmable.

Radio Frequency Identification transponders (RFID) potentially meets most of the requirements for supply chain management. Of the three main categories of RFID technologies, active and semi-active technologies require batteries; this gives them a limited life span and makes them more expensive than the target price of USD 0.05.

Passive RFID transponders consist of only a chip and an antenna. The chip is powered by energy received by the antenna, and data is transmitted back to a reader by modulating the amount of energy reflected. Provided that the chip is small (< 0.5 mm^2) and the antenna is simple, the cost target of USD 0.05 can be achieved. The use of EEPROM and other storage technologies make large ID numbers possible. In addition, data can be added in the field.

Passive RFID technologies are mainly distinguished by the carrier frequencies used. Low Frequency (LF) and High Frequency (HF) cannot meet the 2 m reading range requirement, due to the high signal to carrier ratios typical of these technologies. In addition, data rates are limited by spectrum regulations. Dual Frequency (DF) technology is very promising in terms of performance, but requires two expensive antennas. The reading range of VHF and μWave technologies is limited to less than 0.5 m, mainly by regulatory restrictions.

UHF technology effectively addresses the requirements as stipulated: Spectrum regulations allow good reading ranges in most parts of the world and high data rates can be achieved. Antennas can be physically small and simple, leading to low cost transponders. As a result UHF RFID has been selected by ISO, UCC/EAN and EPCGlobal as the technology of choice for

supply chain management, and several very large corporations (Wal-Mart, the USA Department of Defence, Marks & Spencer, Metro, to name just a few) have committed to large scale roll-outs of UHF RFID.

One of the main requirements for automatic identification, that of high system throughput, cannot be met by most UHF RFID systems, specifically not by the systems selected by ISO, UCC/EAN and EPCGlobal. This is because UHF RFID readers interfere with each other's tag-reader communications, making it difficult (and in some cases impossible) to employ a large number of readers in one RF channel and in close proximity. In this thesis, we analyse the RF environment and RF design parameters of a UHF RFID system, and specifically analyse the interference between readers and tags.

The core of an RFID system is an anti-collision protocol (media-access protocol - MAC) that enables the system to identify large numbers of transponders simultaneously. Only with careful design of this protocol can RF interference be limited while still achieving acceptably high reading rates. The various anti-collision protocols in use today are analysed in a later chapter. This thesis introduces the iP-X protocol developed by the author and shows that the protocol can achieve its design requirements.

The table below shows how the system requirements are systematically broken down into a set of low-level design requirements.

1.4. System requirements allocated to design requirements

From the requirements above, it is useful to derive specific design objectives for the protocol designer. In order to address the system requirements, the designer will use the design objectives to guide the detail design of the protocol, hence the tag chips. *The detail design of the reader does not form part of this thesis.*

The following simplistic allocation indicates how the system requirements are linked to design requirements.

Requirement vs. Solution	Robustness	Compliance	Anti-collision performance	Cost
Long read range	X			
High read rate	X		X	
Narrow band	X	X		
High speed reading	X			
Stochastic algorithm	X			
High saturation level	X		X	
Small chip				X
Low complexity	X			X
Large code space	X			

Table 1: Requirements vs. solutions

Thus, a successful UHF RFID air protocol must aim to address at least the following four design objectives:

- **Robustness.** It must allow for the deployment of large numbers of readers in proximity, with little or no interference between readers and tags, while allowing for maximum throughput. It must perform well in complex RF fields caused by multi-path propagation.

- **Compliance.** It must comply with RF spectrum and electromagnetic interference regulations.

- **Good anti-collision performance.** It must be capable of reading large numbers of fast-moving tags with a high probability of success.

- **Low cost.** The protocol must be implemented on a chip of minimum size, and thus cost.

1.5. The engineering challenge

The engineering challenge lies in the development of a protocol. Such a protocol is implemented in the system by means of specific resources. To meet the detail design requirements, specific resources must be developed - this is the focus of this thesis.

1.5.1. Definition of the engineering problem for this thesis

The need for automated identification in the supply chain must be effectively addressed at both a system and detail design level. As a result, resources must be developed in the form of a UHF RFID protocol as well as tag chips that implement such a UHF RFID protocol. Functionally, this protocol must be capable and its performance requirements (as set out in par. 1.2 above) must be met.

1.5.2. Solution to the engineering problem

The resources that were developed as part of this work effectively address all the requirements for efficient supply chain management (as stipulated above). These resources include an ***effective UHF RFID anti-collision protocol***, a ***realistic simulator*** that predicts the reading effectiveness of the protocol, and tags. This is done in order to reduce risk before continuing with the extremely expensive development of integrated circuits. Finally, a ***series of integrated circuit tag devices*** (tag "chips") that ***cost-effectively*** implement the anti-collision protocol were developed.

1.5.3. Verification of the effectiveness of the solution

- ***Verification*** of the effectiveness of the resources will also address the design requirements as follows: Proof of the protocol's (hence, the tag chip's) functional performance and effectiveness is given in the form of functional verification and simulated performance. Since the actual in-depth detail designs of each of the chips are extremely voluminous, they will not be reproduced in this work. Instead, *"GO / NO-GO"*

results are presented as sufficient proof of the functional capability of the tag chips.

- Proof of the protocol simulator's accuracy will be demonstrated by showing the *high correspondence of actual tag behaviour vs. simulator prediction.* This will prove the usefulness of the simulator in predicting protocol performance and reducing application development risk;

- The system throughput requirement depends on the anti-collision performance of the protocol (i.e. how many tags can be read simultaneously), on the speed at which tagged items can be moved past the reader and how many readers can be operated simultaneously in one facility. *Visual inspection* of the *spectral requirements* and *mathematical analysis* are used to show that the *protocol* developed in this work successfully *addresses the stringent legislation and reader proximity requirements.* Results obtained from the simulator, as well as test setups and pilot installations, are used to quantify the anti-collision performance

- An inspection test shows that the latest successful tag chip is *sufficiently small in terms of area* to reduce *cost to the required acceptance level* in the market. It is generally known that a reduction in occupied area also increases production yield and thus has added advantages.

1.5.4. Validation

Validation of the effectiveness of the UHF RFID solution is illustrated by means of *application testing examples* and is supported by the *actual published (commercial viability) feedback from the users* who apply these chips and the protocol in current applications. The feedback from users gives conclusive evidence that the basic *functional and performance requirements* and *cost constraint were successfully addressed by means of a significant reduction in size* of the latest chips.

For the sake of completeness, it is also shown in this thesis that competing protocols may not address the interference issue as effectively as the protocol developed in this work.

1.6. The iP-X RFID protocol

At the heart of the system lies the iP-X over-the-air communications protocol, a novel Radio Frequency Identification (RFID) anti-collision protocol that outperforms other known protocols in terms of speed, throughput, robustness and the ability to deploy large numbers of readers in close proximity. Its simplicity results in very small chip sizes and very low cost tags, making large-scale exploitation cost effective.

The iP-X Read-only and Read/Write protocols were invented by the author [1],[5] and the iP-X series of UHF RFID chips, as well as their predecessors, were designed, characterised and tested by him. Three of these chips, the P4022, EM4222 and EM4322, are currently in production, with the last two now going into major pilots worldwide [126],[128],[129],[130],[131].

This thesis shows that the iP-X protocol and chips meet all of the above requirements and design guidelines. The contributions of the author, in addition to being the principal engineer on the complete development, specifically include the following:

- The design of Read-only and Read/Write RFID anti-collision protocols that are mutually compatible and adhere to the requirements as set out above. This includes the development and patenting [1],[2],[5] of the basic algorithms, as well as the definition of an encoding scheme and data format that take cognisance of IC implementation limitations.

- Development of an RFID protocol simulator [121]. The simulator provides a realistic model of an RFID application environment.

It was initially used to quantify the protocol's anti-collision performance (See Paragraph 4.8). It is currently used to predict system throughput during the feasibility stage of an RFID application development.

- Implementation of the protocol on chip [112],[113],[114],[116], [117],[123],[124],[147]. Specifically, the following chips were designed in detail and implemented: /*047, H4021, P4022, EM4122, EM4222, EM4322, EM4422, EM4232 and EM4432 (See Chapter 5). These chips were tested and characterised [145], [146],[149],[150]. Three of these chips were successfully put into production while a further two are currently being prepared for production. This process included the drawing up of data sheets [112],[114],[115],[116],[117],[119],[120] and the development of test patterns.

- Development of the reader architecture, implementation of the first prototype readers and providing inputs into the final iP-X reader design and firmware decoders. A hardware decoder [122] was also developed.

- Development of prototype tags based on dipole antennas and managing the research into more complex tag antennas [156],[157],[158].

- Application testing in various supply chain, Electronic Vehicle Identification and Sports Timekeeping applications (See Paragraph 5.4).

- Lobbying the South African regulator (ICASA) [106],[105] and the European regulator (ETSI) [107][108] for a suitable spectrum allocation.

- Providing inputs to the ISO standardisation process [7],[8].

This thesis is organised as follows:

Chapter 2 gives an overview of RFID technologies and their basic operation. It closes with a short history of the development of the iP-X protocol and chips.

Chapter 3 analyses the UHF RF environment, both from a regulatory and electro-magnetic point of view. Various protocol, tag and reader design parameters are derived. The effects of multi-path propagation are investigated. The problem of interference between readers and between readers and tags is analysed mathematically. It is shown that while the minimum separation distance for iP-X readers is acceptable for large-scale industrial deployment, this is not true for other protocols in use today. This theoretical deduction is backed by practical experience. iP-X readers are routinely deployed within 5 m of each other. In contrast, various largely impractical time and frequency multiplexing schemes are proposed for the deployment of readers that comply with the currently proposed international standards.

Chapter 4 analyses various anti-collision protocols from an algorithmic point of view. A brief summary is given of the known protocols in use today, with accent on the Aloha-type stochastic protocols, which fall in the same class as the iP-X protocol. Finally the iP-X protocol is analysed and evaluated by means of a software simulator. It is shown that the iP-X protocol performs very well as an anti-collision protocol, and that the protocol is extremely robust in complex RF fields. The protocol stands out in terms of its ability to handle fast moving tags arriving at a reader at unknown times. Practical measurements have proven the functionality of the protocol and of the simulator modelling.

Chapter 5 describes the practical implementation of the protocol into various tag chips, highlighting RFID specific design aspects. Due to the simplicity of the protocol, very small chip sizes were realised, with the EM4222 at less than 0.5 mm^2 being the smallest multi-read UHF RFID chip currently available. These chips have been tested in practical supply chain, electronic vehicle identification (EVI) and sports applications, verifying the functionality of the protocol in practice. The EM4222 and EM4322 are currently in production and are now going into pilots worldwide, while the EM4422 and EM4432 have been demonstrated to customers, and are currently being prepared for production.

2. BACKGROUND

2.1. Summary

This chapter gives a brief overview and history of electronic identification technologies, with special accent on the UHF RFID development that took place at CSIR during the 1990s and later at PICO Tagging Systems, Inala and iPico Identification. This work culminated in the iP-X protocol and chips.

2.2. Introduction

A passive RFID system typically consists of low cost RF transponders attached to objects, containers, people or animals. Readers transmit an energizing beam to power the tags and receive IDs or product codes from the tags. The data from the readers is filtered and collated and presented to an Enterprise Resource Planning (ERP) system or Management Information System (MIS), for purposes such as tracking goods, identifying vehicles, people or animals, concluding transactions and managing supply chains.

The transponders, popularly called "tags", can be packaged in the form of labels, credit cards or various forms of strengthened industrial enclosures. They can be attached to pallets, containers, crates, boxes, packages, fork lifts, trucks, passenger vehicles, animals, people, etc. They contain no battery, but are powered by rectifying the RF energy received from the reader. Data is not actually transmitted back to the reader; instead the amount of energy reflected ("backscatter") is modulated to carry information. The tags are mostly programmed with unique ID numbers (UIDs), but can also contain product codes, object descriptors or any other data or history that the user wants to associate with an object, vehicle, person or animal.

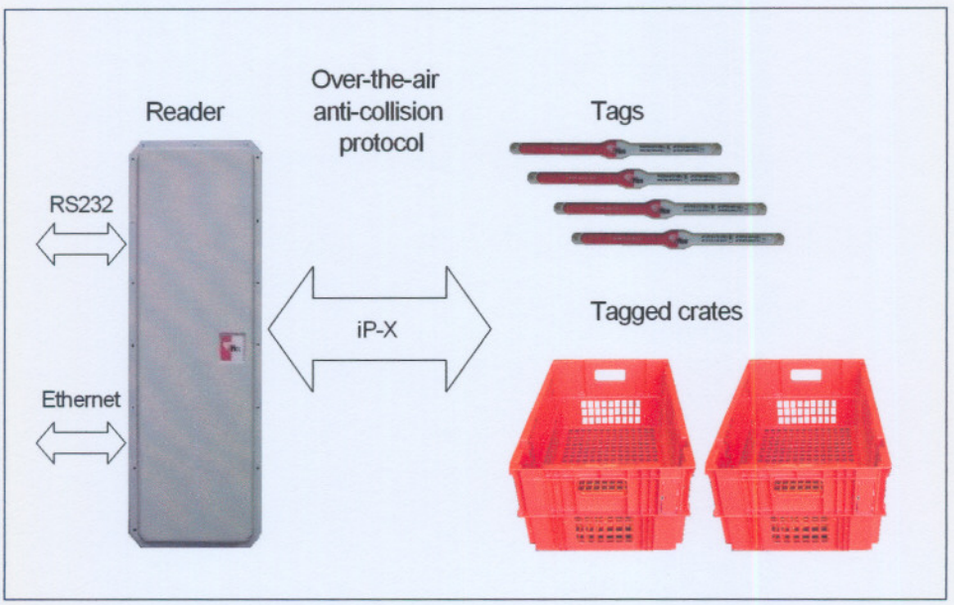

Figure 2: UHF RFID system

Passive UHF RFID, as opposed to barcodes and low frequency (LF) and high frequency (HF) RFID, has been selected as the future technology of choice for supply chain management. It outperforms all other RFID technologies in terms of throughput rate and reading range and promises tremendous savings and increased productivity, through less manual intervention and more accurate capturing of data. It is expected that UHF RFID tags and readers will be deployed on unprecedented scales during the next few years.

With traditional proximity RFID technology, multi-read capability was not an important consideration. However, with long-range tags (> 1 m), it becomes easier to fit several items into a reader's field simultaneously. It therefore becomes necessary to be able to read more than one tag simultaneously ("multi-read"). This is especially true of UHF RFID products, where reading ranges of 10 m and more can be achieved. When more than one tag attempts to communicate with a reader simultaneously, the transmissions could overlap and clash. The tags therefore have to execute an anti-collision protocol to ensure that data reaches the reader successfully.

During the 1990's work in South Africa on UHF RFID and anti-collision protocols was at the forefront of the technology worldwide. This work resulted in the "Supertag" family of multi-read protocols and patents [30] - [41], currently owned by BTG and licensed to Bistar and Samsys, amongst others. Several companies were spawned from this effort, and South African companies and people played a large part in the RFID industry and in the standardisation efforts that took place afterwards. This work also led to the development of the iP-X protocol and the iP-X series of chips and readers.

The Supertag and iP-X anti-collision protocols are based on a stochastic process, i.e. transmission of ID codes take place at random intervals. Tags initiate transmissions ("Tag Talks First" or TTF) upon entering a reader's energy field. Most other protocols use variations of deterministic and non-deterministic binary search algorithms. These protocols require that the reader initiates and steers the anti-collision process by sending appropriate commands to the tags ("Reader Talks First" or RTF).

The iP-X protocols are unique in that no communication from reader to tags is required, resulting in lower bandwidth requirements and less interference. This makes the tag and reader design simple, and makes it possible to deploy readers in close proximity.

2.3. Electronic identification technologies

2.3.1. Bar codes

Bar codes are probably the most ubiquitous of all electronic identification technologies today. The technology was developed during the 1970s but took more than 20 years to become universally accepted. The Universal Code Council and Electronic Article Numbering organizations (UCC Inc. and EAN International) played a major role in standardizing bar codes. Today they are found on virtually every item, case and container.

A bar code consists of a series of lines and spaces printed on a label. It typically encodes a product code, typically a General Trade Item Number (GTIN), but is also used for shipping information, weight, dates, etc. It is read with a scanner, a laser or LED light that is scanned across the label. The reader picks up the reflections from the lines and spaces. Although bar codes are very cheap to apply, costing less than USD 0.01, reading is a manual process. The label has to face the reader, and is easily damaged or obscured by oil and dirt. Reading rates and ranges are low.

2.3.2. EAS

Electronic Article Surveillance or EAS systems could be considered to be single-bit RFID systems in that they can only be enabled or disabled (1 or 0 state). Technologies that are used include Surface Acoustic Wave (SAW) devices, magnetic materials with hysteresis and resonant antennas and diodes. The EAS tags are normally in an enabled state and are then disabled at check-out. Non-disabled tags are picked up at the shop doors to prevent theft. The reading range is about 1 meter.

The cost of EAS tags has up to now been lower than the cost of passive RFID tags. Below the USD 0.10 cost level though, it becomes feasible to use an RFID tag as a smart EAS device, something that can also be used to identify and track an item throughout the supply chain.

2.3.3. Chipless tags

In order to keep the cost of a tag as low as possible, some companies are advocating chipless tags. An EAS system patented by Plows in 1980 [22] already uses a SAW device to create a delay between an interrogating signal and a reply signal. One such system, based on the same SAW technology [72], claims good reading ranges and a large range of ID numbers. Unfortunately, it has no multi-read capability, while the range of numbers currently does not allow for the implementation of large ranges of ID numbers or GTIN codes.

2.3.4. Active and semi-active tags

Active tags are distinguished from passive tags in that they contain their own power source, such as a battery. They mostly consist of a transceiver and a small processor, with the reader consisting of a complementary transceiver. Reading ranges can be very high, even making use of satellites. Data rates are often low and limited by spectrum regulations. The main drawbacks are size, cost and battery life. As transmitted power is usually very low, these tags can be operated in frequency bands that are not suitable for passive tags, e.g. 315 MHz and 433 MHz.

Semi-active tags, or battery-assisted tags, use the backscatter principle to send data to a reader, but use a battery to power the tag electronics in order to improve reading range or to add other facilities, such as telemetry. Unlike active tags, a reader-generated energy field is required to create backscatter. Operation is therefore limited to the same frequency band allocations as passive tags.

2.3.5. Low Frequency (LF)

Passive LF tags operate in the 125 kHz to 134 kHz band. It was the first RFID technology to become widely used through the efforts of companies like Texas Instruments, Trovan, Sokymat, Hughes and EM Microelectronic Marin, mainly for animal identification and sports timing applications. Coupling between reader and tag is inductive (transformer coupling). Most systems are single-read, low range systems. Data rates are limited to below 8 kbit/s and reading range is below 50 cm, mainly limited by signal-to-carrier ratio.

The Tiris product from Texas Instruments overcomes the signal-to-carrier ratio barrier by using a half duplex technology. A power capacitor on the tag is charged during one cycle. During the next cycle the carrier is turned off, and the tag transmits its data back. Reading range is improved to nearly 1 m.

Historically these products did not have a multi-read capability and arrays of readers were used where multiple objects or people had to be read. Lately some slow multi-read products have been introduced.

2.3.6. High Frequency (HF)

HF tags typically operate in the ISM band at 6.8 MHz or 13.56 MHz. This RFID technology was developed to overcome two of the main drawbacks of 125 kHz technologies, namely low data rate and the requirement for a large wire wound coil. Coupling between reader and tag is still inductive, but now the coil consists of just a few windings and can be printed. Reasonably good anti-collision protocols are available, of which the Philips I-Code is the best known.

2.3.7. UHF

Passive UHF RFID is the latest development in RFID technology and has now been accepted as the only technology that can satisfy the requirements of Supply Chain Management. UCC/EAN attempted to repeat their success with the standardisation of bar codes in the field of UHF RFID with their Global Tag (GTAG) initiative. This created an awareness and acceptance of UHF RFID.

The technology offers longer reading range and higher speeds than any other, but is largely limited to line-of-sight applications. Tags could be cheaper than any other RFID technology, mainly due to the ease with which a dipole or folded dipole antenna can be printed or etched.

2.3.8. Microwave

Microwave RFID technology is similar to UHF technology, but due to the smaller capture area of the antennas, reading range is less than one third that of UHF. The tags can be much smaller and therefore cheaper and more user-friendly. Microwave technology is the only option in countries without UHF frequency allocations, e.g. Japan and the Far East.

2.3.9. Dual frequency (DF)

The DF technology [116] was invented by Hennie van Zyl Smit [9] and developed and marketed by iPico Identification. It is a hybrid LF and HF technology, using a 125 kHz carrier for power-up, but replying at 6.8 MHz. It has the power-up range of 125 kHz technologies, but provides an improved signal-to-carrier ratio by replying at a much higher frequency. It achieves reading ranges in excess of 2 m. It can support much higher data rates than 125 kHz technologies and runs the same iP-X anti-collision protocol as iPico's UHF products. The technology is used where UHF RFID fails, i.e. in applications where UHF is absorbed or fails to propagate, for example people and animal tracking, mining, underground reticulation, etc.

2.3.10. Passive telemetry

There is a growing need for passive telemetry tags, i.e. tags that can transmit not only an ID or product code but also an environmental variable e.g. a temperature or pressure. Applications include monitoring tyre pressure, detecting rips in conveyer belts and logging temperature profiles during shipping of fresh produce. While some passive telemetry systems have been proposed [3],[28],[29] and tested, most telemetry tags in use today are active or semi-active, mainly because the sensor and analog to digital converter (ADC) requires more power than can be supplied with an RF power beam, or because the environmental variables have to be monitored or logged even when the tags are not in a reader beam.

2.3.11. Authentication

There is a growing requirement, especially from brand owners that face piracy from grey goods, to use tags not just for product or item identification, but also for item and supply chain authentication. In this case it is important that the tags should not be easy to counterfeit or copy. This implies factory programmed tags and not field programmable tags. In some cases there are additional requirements for encryption or digital certification, typically requiring R/W tags with at least 1 kbit of memory [142].

2.4. Historical perspective

2.4.1. Early patents

Most of the features found in today's passive tags were known and patented more than 20 years ago, putting these features in the public domain today and allowing for easy exploitation. Only the anti-collision protocols as applied to passive tags date from the 1990's and might in some cases be subject to patent protection, although their roots lie in computer network arbitration techniques that are also older than 20 years.

A patent filed by Harris in 1947 [12] describes what is probably the first passive radio transmission system, where a portable station receives its power by radio from a fixed station. Richardson's patent of 1963 [13] also describes a remotely powered transmitter, which seems to be intended for hidden microphone applications.

Albanese's patent filing of 1970 [14] describes a passive reflector that modulates its own radar cross-section (RCS) to send a reply signal in response to an interrogating pulse. Interestingly, it also describes the use of a reflecting plate to reinforce the reflected signal, something that was patented again years later by Intermec [49].

Works *et al* [16] describe probably the first passive UHF tag in their patent filed in 1971. It received power from an L-band microwave interrogator, stored the power and transmitted a coded signal back in the microwave X-band. The transponder was small enough to affix to automobiles, personnel, containers or other objects to be identified. It is also probably the first so-called "on-metal" tag as it contained a metal plate that acted as a shield to preserve the antenna characteristics when the transponder was mounted on a metal surface. In order to reduce the thickness of their transponder Works *et al* also advocated the use a high dielectric constant material between the antenna and the shield. This concept was also later re-patented by Intermec [54]. Their technique of re-transmitting at a different frequency or harmonic

of the interrogating frequency was also later often used e.g Augenblick *et al*'s *Harmonic Communication System* [18], Denne *et al*'s *Passive transponder apparatus for use in an interrogator-responder system* [21] and iPico's DF technology.

It is interesting to note that Works's patent mentions that passive transponders were already well known at the time, but typically used for telemetry, i.e. for transmitting a temperature or pressure value back to the interrogator as an analogue signal instead of digital information.

Kaplan *et al* [19] describe probably the first backscatter system in their patented *Homodyne Communication System* filed in 1975. Their proposed reader architecture is also similar to modern reader architectures as used by Bistar, AWID, iPico and others.

Baldwin *et al* [20] patented what must be one of the first passive telemetry systems in 1976. Their system was based on a passive backscatter transponder that uses "semi-conductor switching means" for varying the load on the antenna.

Probably the first UHF RFID system in the world was developed in Australia at a company called ISD. This work seems to have its roots at the University of Adelaide where Cole *et al* patented a near field magnetic coupling tag as early as 1981 [24]. This was one of the forerunners of today's inductively coupled 125 kHz and 13.56 MHz tag technologies. Later Cole and Turner patented several RFID applications in baggage tracking and sorting [25],[26],[27]. A UHF RFID system marketed by ISD in the early 1990s achieved good reading range and was used in Australia in toll road applications. They seemed to have lost interest in this product though, and it was discontinued in favour of 13.56 MHz products after ISD was taken over by Gemplus.

2.4.2. Development at CSIR

RFID development started in the late 1980s in South Africa at CSIR's National Electrical Engineering Research Institute (NEERI), later Mikomtek, in the IC Design Programme under the leadership of Dr. Theuns Verster, with research into the possibility of using resonant patches to realise chipless tags. When the shortcomings of this approach (limited number range, wide bandwidth requirements) became clear, the focus shifted to chip tags.

The first attempt used a gate array manufactured at EM Microelectronic Marin, a silicon foundry in Switzerland that specialised in low power circuits, and a 64 bit field programmable bipolar ROM using Zener zapping, the */047 device, that was manufactured at the CSIR's own bipolar foundry. At the same time readers were developed that achieved more than 4 m reading range, albeit at quite high power levels (15 W and more). These high reading ranges highlighted the need for an anti-collision protocol. A crude slotted approach was quickly shown to be inadequate, and a stochastic process based on the well-known Aloha protocol was proposed by the author. This approach, called "one way Ethernet" but later known as the "Free-running" protocol, encountered resistance at Mikomtek, but was nevertheless written into the design specification of the proposed H4021 chip in 1992 [112]. An acceleration technique that consisted of acknowledging successful tag transmissions and switching these tags off was invented and patented, later known as the Supertag "Switch-off" protocol. This results in a reduced population of active tags and accelerated detection of the remaining tags. Several other patents on RFID system approaches followed [30],[31],[32],[33],[34],[35],[36]. The Free-running protocol was considered unpatentable, but as was later discovered, Cole *et al* at ISD in Australia had already patented something similar in 1991 [27].

Potential problems with the Switch-off protocol were pointed out and quantified by the author using a software simulator, the forerunner of today's iP-X simulator. These problems mainly involved the incorrect switching off

of tags, which left them undetected. The "Slow-down" variation was proposed as an alternative to Switch-off. In this variation the tag is not switched off completely upon successful detection of its ID, but its reply rate is reduced when it is acknowledged by the reader. This means the ID can still be received later in case of an incorrect acknowledgement, but the active population is still reduced, resulting in almost the same acceleration factor as for the Switch-off protocol.

The H4021 was designed in October 1992 at EM, once again selected for their low-voltage process expertise. It was a 64-bit, field-programmable, EEPROM based device that already included most of the salient features of today's iP-X series chips. It implemented the Free-running, Slow-down and Switch-off protocols. The H4021 exceeded all its design goals and set new benchmarks for low-current consumption and low-voltage operation. Using the H4021 together with an external voltage doubling rectifier from Hewlett-Packard and using X-band Schottky diodes from Plessey, reading ranges in excess of 20 m at reader power levels below 4 W were demonstrated by the middle of 1993.

The author left the CSIR in September 1993 to form a company, Pico Systems, that specialised in high frequency, high complexity IC design. In the meantime the CSIR had sold all its Supertag intellectual property (IP) to BTG, a UK based organisation that specialises in the exploitation of IP. The technology was licensed worldwide, amongst others to Samsys, a Canadian company, and Bistar, a South African company. Samsys later decided to concentrate on multi-protocol readers. Eventually BTG invested heavily in Samsys in 2002. Bistar developed their own chip, implementing a variation of the Switch-off Supertag protocol. Their efforts were bedevilled by the inherent flaws in the Supertag protocol and the way they implemented it. Despite a substantial investment from Richemont and the fact that they realised a single chip UHF tag that set a new low cost benchmark (far below

USD 1.00), they eventually failed and the company ceased operations early in 2003.

In 1998 BTG and CSIR contracted Pico Systems to design a second-generation RFID chip, the P4022, implementing their latest Fast Supertag protocol [37]. The aims were also to bring down the cost of the chip as far as possible by reducing the size of the chip, and if possible, include the RF rectifier on-chip in order to realise a single chip solution. At the same time 125 kHz compatibility was required. These requirements were somewhat conflicting; nevertheless the final chip [113] was about 2.5 mm^2 in size and could be produced in large volumes for about US$0.25. As EM had no Schottky capability at that time, the rectifier had to remain off-chip. The chip made it possible to produce UHF tags for about US$1.00, far cheaper than any other on the market at the time. It was used until recently by iPico to create and sell demonstration systems while working on the iP-X chips.

When 13.56 MHz technology became popular shortly after the development of the P4022, BTG and CSIR lost interest in the P4022. This marked the end of RFID development at CSIR.

Realising the potential of the P4022 chip, the author and three colleagues formed Pico Tagging Systems in 1999 in order to exploit the P4022 commercially. The company managed to get an investment from Inala Technical Investments with the purpose of developing a prototype reader and tags. When this project was successfully delivered, Inala decided to take over Pico Tagging Systems in 2000. By the end of 2001 Inala experienced cash flow problems and could no longer afford the development cost. Instead of allowing the project to be closed down, the author and a few colleagues executed a management buy-out and formed iPico Identification.

A breakthrough came when iPico managed to sign a joint venture agreement with EM early in 2001. According to this agreement iPico and EM would

develop a new series of ultra low-cost RFID chips, with iPico supplying the UHF RFID chip design and air-protocol know-how as well as reader technology while EM would provide silicon manufacturing. This joint venture has led to the development of the iP-X series of chips during 2002.

2.5. Publications and patents

Very little has been published on RFID, especially UHF RFID, in scientific refereed journals [10][11]. The few publications that have been published are mostly of a marketing nature or press releases. Internet publications on RFID are mainly paid-for publications and can therefore not be considered to be neutral and impartial.

The most useful information comes from patent applications and publications. This is understandable, given the potential size of the RFID market. Patents play an important role in protection the intellectual property of inventors and companies and their investments in developing new products.

What is somewhat distressing is the way in which known techniques and methods get patented, as this can lead to slower exploitation and standardisation of the technology. Good examples here are some of the patents of Intermec and Lucent. Take for example the patents of Brady *et al* of Intermec [54],[55]. The use of reflectors in antennas has been known for many years, similarly the use of high dielectric constant materials to reduce the size of conformal patch antennas. Yet these two patents have been granted, presumably because the application to RFID is considered new. However, one could argue that a dipole antenna remains a dipole antenna, that an RFID system is just another RF system, and that any antenna expert would consider the use of reflectors and high dielectric materials to enhance the performance of antennas if necessary. Similarly, Shober *et al*'s patent filed in 1996 [44] seems to patent technology that was well known at the time. It is predated by other patents, notably those of Kaplan *et al* [19] and Baldwin *et al*

[20], and was mostly already present in the H4021, which was designed in 1992.

This frivolous patenting and granting of patents creates a minefield of uncertainty in the market. Violating a patent can prove to be very expensive and sometimes fatal to a company, as has been shown before, cf. Trovan vs. Sokymat and Polaroid vs. Kodak [141].

Chapter 3

3. RF ENVIRONMENT

3.1. Summary

This chapter analyses the RF environment and derives specific design requirements for a UHF RFID reader. It investigates the limitations due to the RF regulatory environment and brings to the fore possible interference considerations when large numbers of tags and readers are deployed in this environment. Also in this chapter, a spectral and theoretical analysis of the effects of interference shows the inherent drawback of protocols where the backscattered information spectrum overlaps the reader transmit spectrum. It is further shown that a technology barrier exists in the form of required reader spacing when not using a protocol that effectively separates the tag backscatter data from the reader transmit spectrum. This limitation is overcome using the protocol developed in this work.

Actual throughput that can be achieved in a multi-tag and multi-reader environment depends critically on the choice of anti-collision protocol. In order to understand the implications of the anti-collision protocol on the RF *characteristics of the system, it is necessary to understand the basic* RF *operation of such a system, and to appreciate the limitations placed on the system by regulatory authorities.*

3.2. Introduction

When an RF expert or design engineer is confronted for the first time with the RF requirements of a UHF RFID system, namely to transmit enough RF power to power a tag at some distance (several meters) while at the same time and at the same frequency receive a reflected signal (modulated radar echo), the typical reaction is that it is impossible. In practice, of course, it is possible and reading ranges of several meters are easily achieved nowadays.

A UHF RFID system can be considered to be similar to a CW radar system. The reader transmits a power beam in the form of a CW carrier. This is reflected off the tag and the echo or backscatter is received by the reader (See Figure 3). In order to transmit a code, ID number or other data to the reader, the tag modulates its radar cross section (RCS) by changing its input impedance. This affects the matching of the antenna and modulates the amount of energy that the antenna absorbs or reflects.

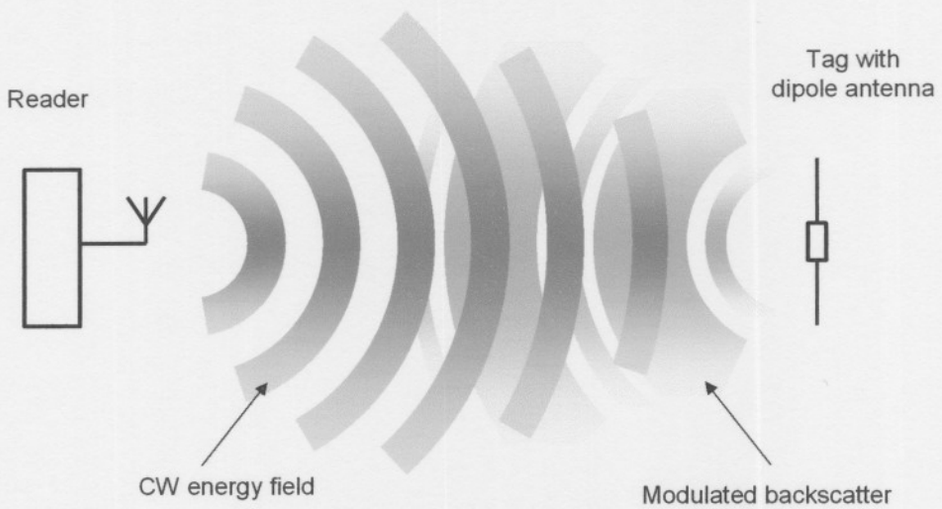

Figure 3: RFID basic principle.

In the iP-X chips the input impedance is modulated by switching a MOSFET transistor across the antenna. Other manufacturers switch a varactor (e.g. Palomar [68]), but the overall effect is the same: The reader, operating as a CW radar, sees a target that is varying in size (like an aircraft that is flapping its wings). The variation in RCS can be detected to extract data from the reflected signal.

Another analogy is that of the heliograph systems used amongst others by the Boer forces a hundred years ago to communicate with each other. In the case of the heliograph a mirror is used to reflect sunlight to the receiver in a coded

manner in order to transmit information. The analogy is even closer when the signalling mirror is directly in line with the sun, so that the observer (receiver) has to try to detect the coded light pulses while looking straight into the sun.

The UHF band turns out to be an ideally suited band for UHF RFID systems. As the operating frequency is increased, tag and reader antennas become smaller and user-friendlier. Unfortunately, the effective capture area of the tags (antenna aperture) is proportional to the square of the wavelength, so that a tag can capture less energy at higher frequencies. At UHF frequencies around 915 MHz, the tag size gets small enough to be practical, while enough energy can be still captured to achieve useful reading ranges. The upper limit for passive tags probably lies at 2.45 GHz, beyond which reading ranges become too short to be useful. As it turns out, there is also spectrum available in the UHF band in most countries of the world, with the exception of Japan[1] and possibly other Region 3 countries, where spectrum is only available at 2.45 GHz.

3.3. Regulatory environment

Radio spectrum is a scarce and valuable commodity. It is jealously guarded by regulatory bodies and government institutions in every country of the world. Although this may seem a "non-technical" issue, it is still one of the most challenging issues in RF systems that will eventually influence the actual design of a system - it must therefore be analysed and treated as input to a technical design. Unfortunately, there is very little standardisation, although, at least in Europe, there are currently moves towards harmonisation. The main aim of the regulatory bodies (FCC in the USA, ETSI in Europe, ICASA in South Africa, ACA in Australia, etc.) is to protect legitimate users of the RF spectrum from interference from "rogue" users and transmitters and to assign spectrum bands for particular applications to allow inter-operability (e.g. the

[1] Japan is reportedly currently investigating a frequency allocation at 950 to 956 MHz.

spectrum allocations for GSM). Preference is often given to emergency and military services, civil communications, and, of course, paying users. UHF RFID does not fall into any of the above categories and as such it has to take a back seat at present.

The world is roughly divided into three regions, Region 1 being Europe and Africa (lead by ERC), Region 2 being the Americas (lead by the FCC of the USA), and Region 3 being the Far East. However, in each of these regions, each country still has its own local spectrum regulations.

RFID systems are typically lumped together with Short Range Devices (SRDs), which include remote controls such as garage door openers and remote alarm buttons and medical implants. Unlike other SRDs, passive RFID systems operate at relatively high RF power levels. In reality current regulations worldwide only allow for the regulation of intentional or unintentional active transmitters and as such covers RFID readers but not passive RFID tags. Testing of readers is also problematic, as their spectrum usage depends largely on whether or not tags are present.

In the USA the FCC has allocated an ISM band from 902 to 928 MHz where fairly large transmitted power levels are allowed. This makes it easy to deploy RFID systems in the USA and long-range reading can be achieved. In Europe this band is occupied by GSM and only a small low power band is available between 860 and 870 MHz. UCC/EAN, in support of their GTAG initiative, has lobbied the ERC for increased spectrum allocations, claiming that it puts European companies at a disadvantage compared to USA companies, especially in SCM. The European regulator is currently investigating a 2.5 MHz, 2 W eirp allocation in the 860 - 870 MHz band.

In South Africa the situation has been quite complex. Although GSM is used in South Africa, the band between 915 and 921 MHz has actually not been allocated until now. The Government Gazette of 27 December 1996 No.

17701 Par. 3.9.9 proposed that spectrum from 915.2 to 915.4 MHz be allocated to passive tags. This was done as a part of the SABRE project to harmonise SA spectrum regulations with Europe [110]. SABS WG1 of TC74 (National Committee (TC 74: Communication technology)) put in proposals for UHF RFID spectrum allocations similar to those available in Europe and the USA [111]. The author made similar proposals to ICASA in response to an invitation (Notice 891 of 2002) for representations to an Enquiry on Short Range Devices [105],[106]. Eventually an allocation was published in the South African Government Gazette of 7 June 2002 No. 23491 that included two allocations: One similar to the European allocation between 869.4 and 869.65 MHz, but with lower allowed power (500 mW eirp instead of 500 mW erp), and one between 915.2 and 915 .4 MHz with unspecified power [104].

The current main spectrum allocations for UHF RFID can be summarized as follows:

- Europe (ETSI 300 220-1, CEPT/ERC/REC 70-03): 0.5 W erp (0.81 W eirp) at a 10% duty cycle between 869.4 and 869.65 MHz [97],[98],[99],[100].

- USA unlicensed (FCC Part 15): 4 W eirp frequency hopping between 902 and 928 MHz. At least 50 channels with maximum 0.4 s dwell time [95].

- USA site licensed (FCC Part 90): 30 W eirp (frequency coordinated) (Maximum 3 W conducted and maximum 10 dBi gain antennas) [96].

- South Africa (ICASA): Unspecified power between 915.2 MHz and 915.4 MHz and 500 mW eirp between 869.4 and 869.65 MHz [104].

- Australia (ACA): 1 W eirp spread spectrum between 918 MHz and 926 MHz and between 2.4 GHz and 2.45 GHz [102].

- Canada: Similar to the USA [101].

The spectre of hundreds or thousands of unlicensed RFID readers, all transmitting at relatively high powers, is haunting many current users and regulatory bodies. Should such systems be accepted and put widely into use, they would be very difficult to control and limit. Regulatory bodies, especially in South Africa and Europe, but also elsewhere, have therefore been moving with caution.

The system developed by the author is a possible solution to the above problem, as it uses a very narrow band. It can quite easily operate in a single 12.5 kHz channel, and only one channel is required countrywide or even worldwide. This is a vast improvement compared to the spectrum requirements of e.g. RTF RFID systems. One known system (Matrics [133]) requires at least 1 MHz of bandwidth in the USA, and must be limited in terms of performance (baud rate, reading rate) in order to operate in the 250 kHz band that is currently available in Europe.

3.4. Protocol implications

The choice of over-the-air protocol and modulation techniques has a major impact on the spectrum requirements of the system. Chapter 4 examines the actual protocols in more detail. Of interest in this chapter is the impact of the protocol on the RF requirements, some of which have already been mentioned in the preceding section.

3.4.1. Protocol

The iP-X read-only protocol requires no communication whatsoever from the reader. The reader only transmits a pure CW signal and listens for backscatter replies. The reader bandwidth can be arbitrarily narrow and can operate in a single 12.5 kHz channel. The backscatter spectrum is determined by the baud rate and encoding technique, but the power levels are low enough that interference is not a concern. The only concern is that transmitters in

adjacent channels can interfere with the backscatter signal. This possible interference must be accepted. Luckily the pseudo random (almost spread spectrum like) nature and built-in redundancy of the protocol mitigates this problem. The reader and backscatter spectra can be widely separated, so interference from other readers can be filtered out.

The iP-X read/write protocol does require commands from the reader to the tags. These employ 10% to 100% AM at 16 kbaud/s. It is expected that writing to tags will often only take place once at short range in controlled circumstances. This is especially true of applications where the tags are used as one time programmable (OTP) devices, such as EPC applications. It might be required to read additional programmed data other than the ID from these tags during normal operation. This requires on average only one command from reader to tag, so the power content will on average be low. Interference from nearby readers can be expected, but once again, the built-in redundancy of the protocols will help.

Protocols based on the Supertag patents [28],[31],[32],[33],[34],[35],[36] make use of acknowledgement signals from the reader to the tag in order to speed up the protocol. These acknowledgments take the form of single or multiple pulses at appropriate times and occur typically once per tag transmission at baud rates comparable to the tag baud rates. These acknowledgement pulses create additional spectral components that overlap with the backscatter spectrum.

There are various binary search and slotted protocol algorithms in use [48],[62],[68],[91],[76]. These all have one thing in common – the reader steers the anti-collision algorithm by means of commands to the tags. In order to reduce the required reader bandwidth, these commands are typically transmitted at slower baud rates than the backscatter. The power and spectral content is nevertheless much larger than that of the Supertag protocols and iP-X protocol.

The worst-case protocol as far as bandwidth requirements are concerned, is probably the one utilised by Matrics. This protocol depends on extensive reader-to-tag communications, at the same baud rate as the backscatter. More than 1 MHz bandwidth is required for full performance, and the protocol has to be slowed down to meet European regulatory requirements.

3.4.2. Encoding

The iP-X protocol implements a pulse position encoding for both the up link and the down link. The encoding is based on Manchester encoding (see Figure 4). A pulse in the first half of a bit period indicates a ONE while a pulse in the second half indicates a ZERO. The encoding can also be considered to be a transition encoding, with a pulse interval of 0.5 bits indicating a 0-1 transition, a pulse interval of 1 bit indicating no transition, and a 1.5 bit interval indicating a 1-0 transition. A 2 bit interval code violation followed by a ONE is used for synchronisation. Eight start bits allow for automatic gain control (AGC) and filter time constants or for a phase locked loop (PLL). It has spectral components from about half the baud rate to about four times the baud rate, i.e. a 64 bit/s baud rate will have spectral components from about 32 kHz to about 256 kHz, with a strong spur at 128 kHz (caused by the ¼ bit pulses).

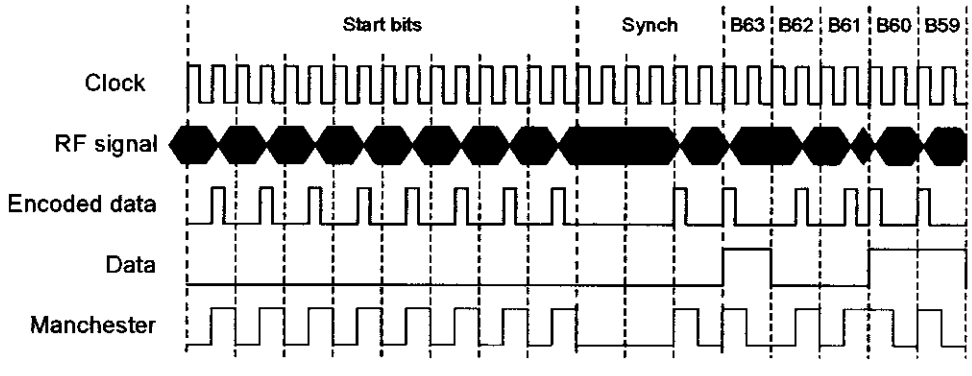

Figure 4: Pulse position encoding

ISO 18000-6 [86] specifies either Manchester or Pulse Interval Encoding (PIE). PIE encoding requires a similar bandwidth to the iP-X encoding scheme but has a drawback in that the word lengths depend on the contents. Manchester encoding requires about half the bandwidth at the same baud rate than PIE or iP-X but requires more charge storage capacity on-chip (See Par. 5.2.3).

3.4.3. Baud rate

Bandwidth requirements (reader and tag backscatter) are directly proportional to baud rate. Thus 64 kbit/s tags require about 250 kHz of bandwidth (See Par. 3.4.2), while the 256 kbit/s tags will require about 1 MHz.

3.4.4. Modulation technique

The reader transmits its commands at high power, and is limited by regulatory and other requirements as far as bandwidth is concerned. The iP-X protocol does not require the reader to transmit any commands, so this has no real implication for it. Other manufacturers are not in this position and have used various techniques to reduce the spectral content of their reader transmissions. The most common technique that is used is to reduce the modulation index. This directly reduces the power content. A second technique controls the edge transition times. Increasing the rise and fall times reduces the bandwidth. A technique pioneered by Intermec and accepted in ISO 18000-6 [84] to further reduce the spectral content is to use a raised cosine function for the edge transitions.

3.5. Powering a tag

In a passive RFID system, unlike a CW radar system, the transmitted beam does not only illuminate the tag, it also powers the tag. The energy incident on the tag antenna is rectified and used to power the tag electronics.

The power density E_r at a distance r from the reader is given by:

$$E_r = \frac{G_{Tx} P_{Tx}}{4\pi r^2} \qquad \text{- (1)}$$

where:

G_{Tx} is the gain of the reader transmitting antenna, and
P_{Tx} is the power transmitted by the reader, and
$G_{Tx}P_{Tx}$ is the Effective Isotropically Radiated Power (EIRP) of the reader.

The tag antenna captures a portion of this energy, proportional to its effective area A_{eff}:

$$P_{Tag} = \frac{G_{Tx} P_{Tx} A_{eff}}{4\pi r^2} \qquad \text{- (2)}$$

The effective area of an antenna is given by:

$$A_{eff} = \frac{\lambda^2 G}{4\pi} \qquad \text{- (3)}$$

where G is the gain of the tag antenna (2.1 dBi for a half wave dipole).

The power received by the tag is therefore given by:

$$\begin{aligned} P_{Tag} &= G_{Tx} P_{Tx} G_{Tag} \left(\frac{\lambda}{4\pi r} \right)^2 \\ &= EIRP \cdot G_{Tag} \left(\frac{\lambda}{4\pi r} \right)^2 \end{aligned} \qquad \text{- (4)}$$

and the path loss is given by:

$$\frac{P_{Tag}}{P_{Tx}} = G_{Tx} G_{Tag} \left(\frac{\lambda}{4\pi r} \right)^2 \qquad \text{- (5)}$$

The iP-X series UHF tags consumes less than 5 μW of DC power. The graphs in Figure 5 below were obtained by inserting this number into Equation 4 and calculating the power-up range that can be achieved for various transmit power levels at 915 MHz and 2.45 GHz. For comparison purposes the graph for a Matrix tag that consumes 50 μW [133] is also shown. This seems to indicate that more than 10 m reading range should be achievable in Europe and 30 m reading range should be achievable in the USA, provided that power-up was the limiting factor that determines reading range.

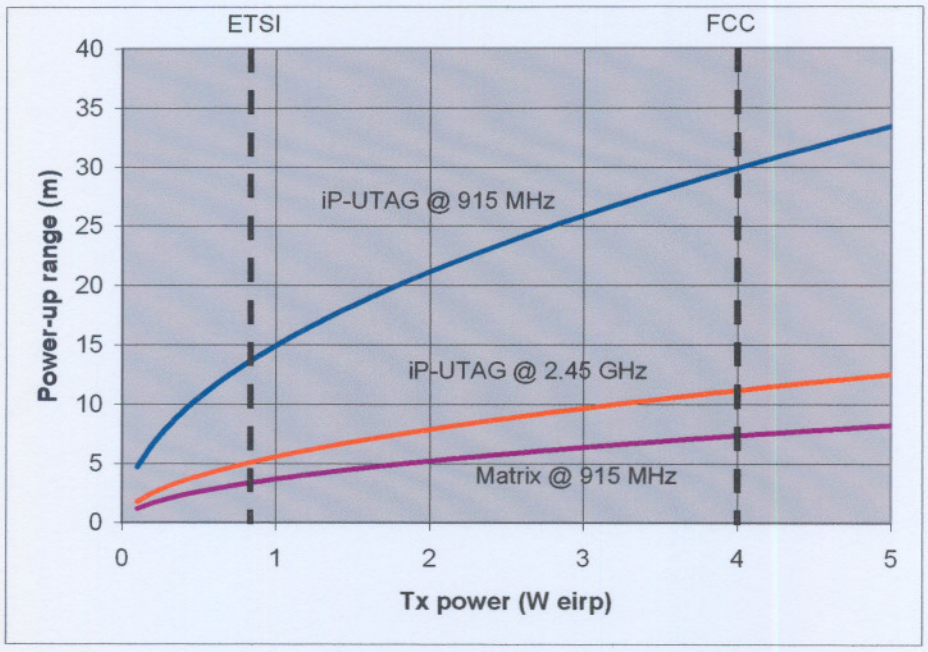

Figure 5: Theoretical power-up range based on received power.

Unfortunately, it is not the received power, but rather the received voltage, that determines the power-up range. The voltage on the tag is given by:

$$P_{Tag} = \frac{V_{Tag}^2}{R} \qquad \text{- (6)}$$

where R is the impedance of the tag antenna. R is typically 73 Ω for a half wave dipole, but can be tuned as high as 600 Ω.

Substituting (6) into (4) gives:

$$V_{Tag} = \sqrt{EIRP \cdot G_{Tag} \cdot R} \cdot \frac{\lambda}{4\pi r} \qquad \text{- (7)}$$

The H4021, P4022 and the latest iP-X series UHF tag chips all require about 1.2 V to power-up. Because of the voltage doubling rectifier that is used, only about 0.6 V amplitude is required at the antenna ports. Multi-path effects can result in a doubling of the voltage received. The graphs in Figure 6 below was obtained by inserting these numbers into Equation 7 and calculating the power-up range that can be achieved for various transmit power levels at 915 Hz. These graphs give more realistic power-up ranges of 2 m to 3.5 m in Europe and 4 m to 7.5 m in the USA.

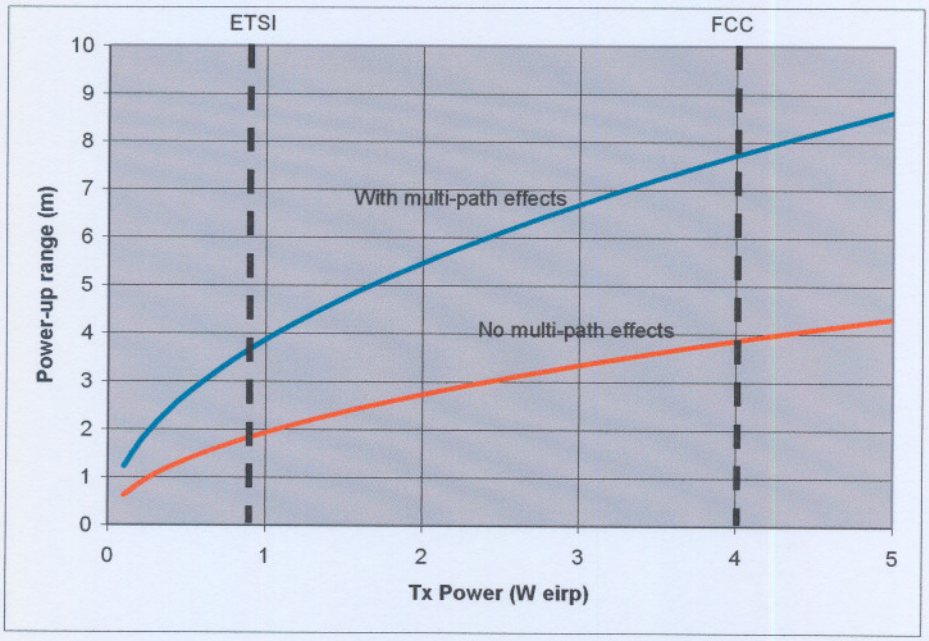

Figure 6: Theoretical power-up range based on received voltage.

Measurements were made to support the theoretical predictions of range. These actual measured reading ranges for a dipole tag and a credit card sized tag are plotted in Figure 7 below. The measured results compare reasonably well with the theoretical values plotted in Figure 6. The difference in reading range between the two types of tags is due to the difference in antenna gain and therefore effective capture area (the credit tag uses a folded dipole).

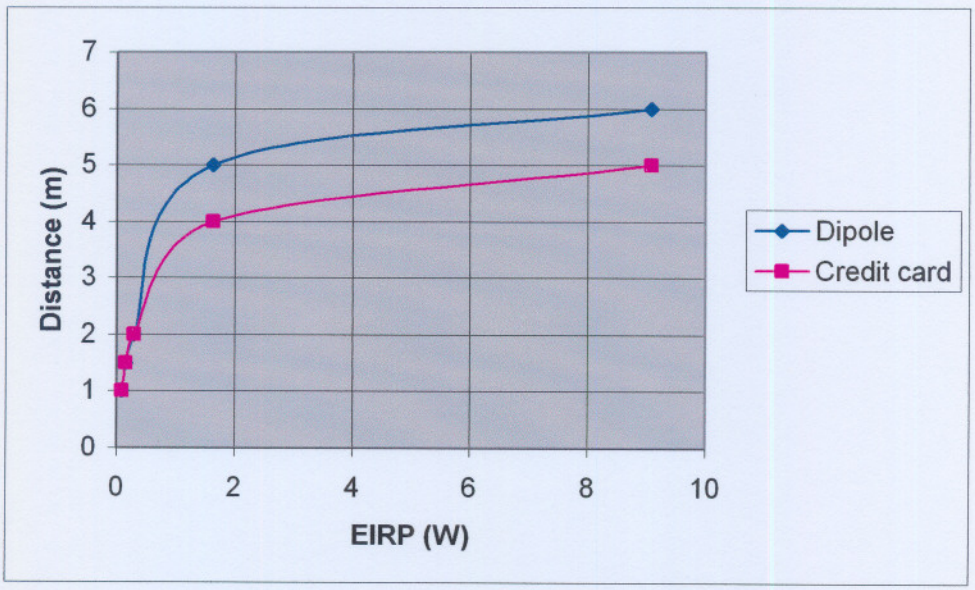

Figure 7: Measured reading range for two different types of tags

3.6. Backscatter

The strength of the backscatter signal is given by the radar equation:

$$P_{Rx} = \frac{P_{Tx} G_{Tx} G_{Rx} \lambda^2 \sigma}{(4\pi)^3 r^4} \qquad \text{- (8)}$$

Where:

P_{Rx} is the received power

P_{Tx} is the transmitted power

G_{Rx} is the gain of the receiving antenna

G_{Tx} is the gain of the transmitting antenna

σ is the radar cross-section (RCS) of the tag (typically about 10 cm^2)

If $G_{Tx} = G_{Rx} = G$ equation (3) can be simplified to:

$$P_{Rx} = \frac{P_{Tx} G^2 \lambda^2 \sigma}{(4\pi)^3 r^4} \qquad \text{- (9)}$$

and the path loss is then:

$$\frac{P_{Rx}}{P_{Tx}} = \frac{G^2 \lambda^2 \sigma}{(4\pi)^3 r^4} \qquad \text{- (10)}$$

Note that both equations (4) and (9) contain the factor λ^2, i.e. both the power received by the tag and the strength of the backscatter signal is proportional to the square of the wavelength and therefore inversely proportional to the square of the frequency. This is because the effective aperture is proportional to the square of the wavelength and is the main reason why RFID systems perform worse at higher frequencies. At 2.54 GHz (as allowed e.g. in Japan) the tag receives almost an eighth of the power at the same distance compared to 915 MHz, or about a third of the voltage. In other words, reading range at 2.54 GHz will be about a third of the reading range at 915 MHz at the same transmitted power levels. Given the fact that quite often, e.g. in the USA and South Africa, much higher powers are allowed at 915 MHz, it is clear why UHF frequencies are so attractive for RFID.

3.7. Reader design parameters

Using the equations from Par. 3.5 and Par. 3.6 above a number of reader design parameters can be calculated. Of special interest are the required sensitivity, dynamic range and linearity (1 dB compression point) of the reader.

The iP-X reader architecture is shown in Figure 8 below. A CW signal is transmitted at the transmit (Tx) antenna. The backscatter is received at the

receive (Rx) antenna and mixed in quadrature with the same signal that was transmitted (effectively a quadrature direct down conversion receiver).

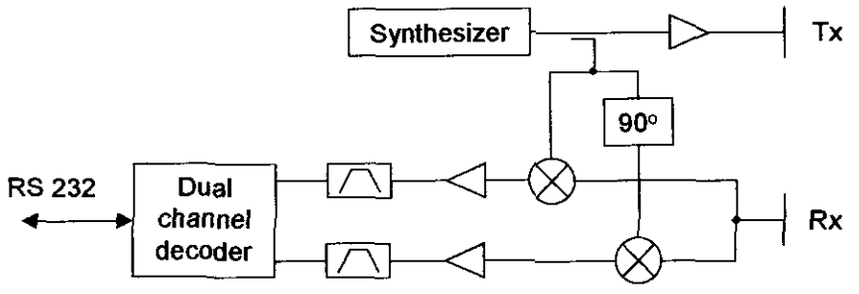

Figure 8: iP-X reader architecture

3.7.1. Sensitivity

From (4), (6) and (10), ignoring multi-path effects and assuming an RCS of 10 cm^2 and an antenna impedance of 600 Ω, the received power at maximum range can be calculated. The required sensitivity varies from about –67 dBm for a European 500 mW erp reader to –74 dBm for a USA 4 W eirp reader, both with 6 dBi antennas.

3.7.2. Dynamic range

The dynamic range of the reader is determined not so much by the maximum strength of the backscatter signal, but rather the strength of the reflection from the object on which the tag is mounted. Also to be considered is the isolation between the Tx and Rx antennas.

Using (4) with the total distance between Tx and Rx equal to $2r$ and assuming a perfect reflector at distance r from the reader, the reflected power received is given by:

$$\begin{aligned} P_{Rx} &= G_{Tx} P_{Tx} G_{Rx} \left(\frac{\lambda}{4\pi(2r)}\right)^2 \\ &= G_{Tx} P_{Tx} G_{Rx} \left(\frac{\lambda}{8\pi r}\right)^2 \end{aligned} \qquad \text{- (11)}$$

And with $G_{Tx} = G_{Rx} = G$ as before, the path loss is given by:

$$\frac{P_{Rx}}{P_{Tx}} = \left(\frac{G\lambda}{8\pi r}\right)^2 \qquad \text{- (12)}$$

From (10) and (12) the relative strengths of the backscatter and the reflected signal can be calculated:

$$\frac{P_{backscatter}}{P_{reflected}} = \frac{\sigma}{\pi r^2} \qquad \text{- (13)}$$

This ratio improves as the distance between tag and reader is reduced. However, the worst case arises when a nearby object reflects a strong signal and swamps a tag that is far away.

From (11) the reflected signal strength can be calculated as a function of transmitted power and distance. Assuming a worst-case separation of 30 cm (iPico standard practice) between a perfect reflector and the reader (excluding antenna gain), the path loss can be calculated to be about 27 dB. The path loss is much less if high gain antennas are used. With 7 dBi antennas the path loss drops to 13 dB. In Europe, with a 500 mW erp (800 mW eirp or 29.1 dBm eirp) transmitter and 7 dBi antennas, the received reflected power is 9.1 dBm. In the USA with a 4W eirp (36 dBm eirp) transmitter and 7 dBi antennas, the received reflected power is 16 dBm.

It is important that any coupling between the Tx and Rx antennas must be less than the minimum path loss, otherwise the required linearity and dynamic range of the reader front-end will be even more stringent. In a well-designed reader isolation of between 30 dB and 55 B can be achieved. The iP-X readers routinely achieve about 30 dB. For battery-assisted tags more sensitivity is required and therefore better isolation. With careful adjustment 55 dB can be achieved.

Using the above equations and arguments, the minimum separation distance between two readers facing each other can be deduced. Assuming that the reader can operate with an isolation of 30 dB with a margin of 3 dB, the minimum separation is the distance at which the path loss is equal to 27 dB. Substituting this value into Equation (12) and solving gives a minimum separation of approximately 3 m.

There is a tendency to want to use a low noise amplifier (LNA) in the Rx front-end. An LNA would improve sensitivity and reduce the noise figure (NF) requirements for the mixer. However, as shown before, sensitivity is not a problem with passive tags. Instead an LNA would amplify the received signal and therefore increase the dynamic range requirements of the mixer. One exception is readers intended for use with battery-assisted tags, where more sensitivity and better isolation between the Tx and Rx antennas are required. For these readers the minimum separation distance will also be higher. iP-X readers use 20 dB of additional gain in their battery-assisted tag readers. This increases the minimum separation distance to 30 m.

As mentioned before, an alternative architecture, used e.g. by AWID [75] and Bistar, involves the use of a single antenna together with a circulator or directional coupler. The main problem with this architecture is that, even with a very good coupler, the isolation between Tx and Rx and the required dynamic range is determined by the antenna matching. Considering that 15 to 20 dB is normally considered to be a good match, it is clear that this architecture places much more severe requirements on the mixer.

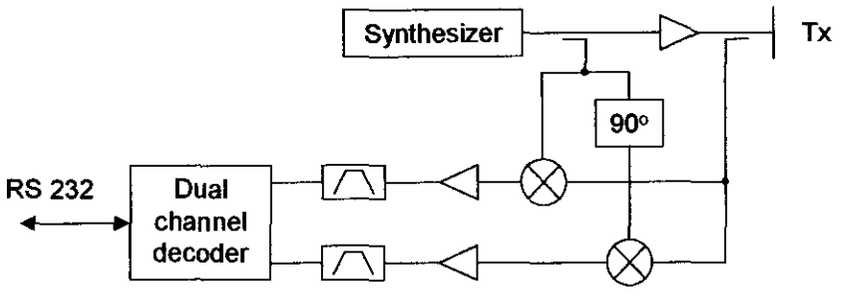

Figure 9: Alternative reader architecture using single antenna with directional coupler.

3.7.3. Phase noise

It is interesting to note that since we are mixing the received signal with the same signal that is transmitted, phase noise performance is not very important.

3.7.4. Frequency accuracy and stability

In order to deploy several readers in close proximity, it is important that the carrier frequency be accurate and stable over time and temperature. Ideally all readers should run at exactly the same frequency (slaved to the same clock). Any differences between reader frequencies appear after the mixers as a difference (Doppler) component. This component should be far enough away from the data spectrum, so that it can be effectively filtered out. IP-X readers are specified ± 1 kHz with a 5 ppm stability over temperature, so the maximum difference component is less than 7 kHz. This is far enough away from the 64 kbit/s spectrum and even further from a 256 kbit/s spectrum (see Figure 10) below.

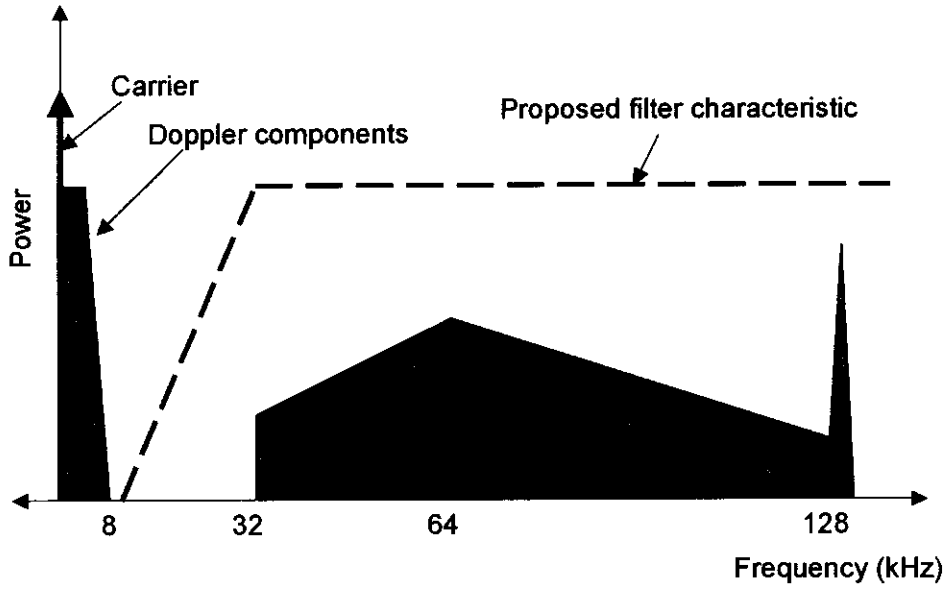

Figure 10: Separated Doppler and data spectra.

3.8. Interference between readers and tags: spectral analysis

Passive RFID protocols can be partitioned into two opposite groups, namely "Tag Talks First" (TTF) and "Reader Talks First" (RTF) protocols. With a RTF protocol, the reader initiates communication with the tags. Tags are typically woken up with a "wake-up" command and stay quiet until they recognise such a wake-up command. With a TTF protocol, the tag initiates communications with the reader. Tags are quiet outside a reader beam, but announce their presence upon entering a reader beam. RTF and TTF systems are mutually incompatible. TTF tags can interfere with the anti-collision protocol of RTF tags, while RTF readers can interfere with the backscatter of both TTF and RTF tags.

The term "tag pollution" has been coined by proponents of RTF systems for the scenario where TTF tags from different manufacturers all clamour for attention, and in the process jam each other and interfere with their respective anti-collision algorithms. Lately, a new concern has arisen, namely that of "reader pollution" or "reader collision" [78]. In scenarios where several RTF

readers, possibly from different manufacturers, have to operate in proximity, there is a real risk that the readers would interfere with each other and with tag transmissions. Examples are warehouses with several docking bays next to each other and production lines where tags are read at several points along the manufacturing process.

Engels at the MIT Auto-ID Center [78] attempted to solve the problem through partitioning of the allowed spectrum and through various means of frequency allocation or power limiting. This approach fails immediately in Europe, as there is not enough bandwidth to allow partitioning. As will be seen below, even in the USA this approach is not likely to succeed for most protocols as the "interrogation zone" is much larger than expected.

The "tag pollution" concept and an insistence on RTF protocols probably originally started for historical, political and business reasons, rather than good technical reasons. We shall now analyse tag and reader pollution and show that the iP-X protocol outperforms other protocols in terms of interference levels. The iP-X system is, to our knowledge, the only system that can be deployed in large numbers in close proximity.

3.8.1. "Reader Talks First"

The basic idea behind RTF is that tags remain quiet until specifically addressed or commanded by a reader, i.e. tags are "woken up" by a specific command. The mere presence of a signal from a reader, such as a CW power beam should not wake the tag. Assuming that a standard wake-up sequence can be agreed upon, tags from different manufacturers that are executing different anti-collision protocols can co-exist – only a subset from one manufacturer will be woken up at any specific time, while the rest would not interfere with the anti-collision protocol and other communication between reader and tag.

The main drawback with RTF protocols is that RTF readers, unless they are alerted to the presence of tags by some other means (electronic, mechanical or manual), have to poll continuously for tags, i.e. they have to transmit wake-up commands at regular intervals to detect the presence of tags. This polling can be a powerful source of interference. In addition, most, currently commercially available RTF anti-collision protocols employ some form of deterministic or non-deterministic binary tree traversal algorithm. These algorithms are particularly demanding as far as bandwidth in concerned.

3.8.2. "Tag Talks First"

A TTF tag announces itself by transmitting an ID when it detects the presence of a reader. In passive tags the reader is detected merely by the fact that the tag powers up when it enters the reader beam. Once the reader has received the tag ID, it can command the tag to switch off or otherwise communicate on a one-to-one basis with that tag.

It is important that the initial ID announcement takes place in a manner that allows for multiple tags to be in the beam simultaneously. In currently available products such as the P4022 chip and the iP-X series chips, the ID is transmitted in a pseudo-random manner with an average duty cycle that is low enough to allow for the detection of large numbers of tags, while still fast enough to achieve a reasonable throughput rate. Duty cycles of 1:500 are suitable for most supply chain applications and allow for the detection of several hundred tags simultaneously (See Chapter 3).

TTF tags can typically co-exist with other TTF tags, mainly because of the inherent redundancy in their pseudo-random protocols. Because no polling is required, reader interference can be much lower than for RTF systems. However, this will depend on the protocol itself. If the protocol requires intensive reader-to-tag communications, such as commands to traverse a binary tree or commands to set protocol parameters, significant interference can still be generated by the reader.

3.8.3. "Tag Only Talks"

The basic iP-X protocol is what could be called a "Tag Talks Only " (TTO) protocol. Like a TTF tag, a TTO tag announces itself to the reader by transmitting an ID when it detects the presence of a reader. However, the reader never transmits any data or acknowledgements. It only listens and builds up a list of tag IDs as they are received. Because no polling is required and no commands are ever sent by the reader, reader interference is minimal.

3.8.4. Bandwidth comparison

All RTF and most TTF protocols require larger reader bandwidths than a basic read-only TTO protocol. The ISO 18000-6 RTF protocol standard specifies 200 kHz channels, while some read-only RTF tag products, such as the Matrics products, require even more. In comparison, a TTO protocol can operate in a single 12.5 kHz channel since no reader modulation takes place. This is an important consideration for Europe and countries outside of the USA.

Measured spectra for an iP-X reader is shown in Figure 11 below. As can be seen, a very narrow bandwidth is required.

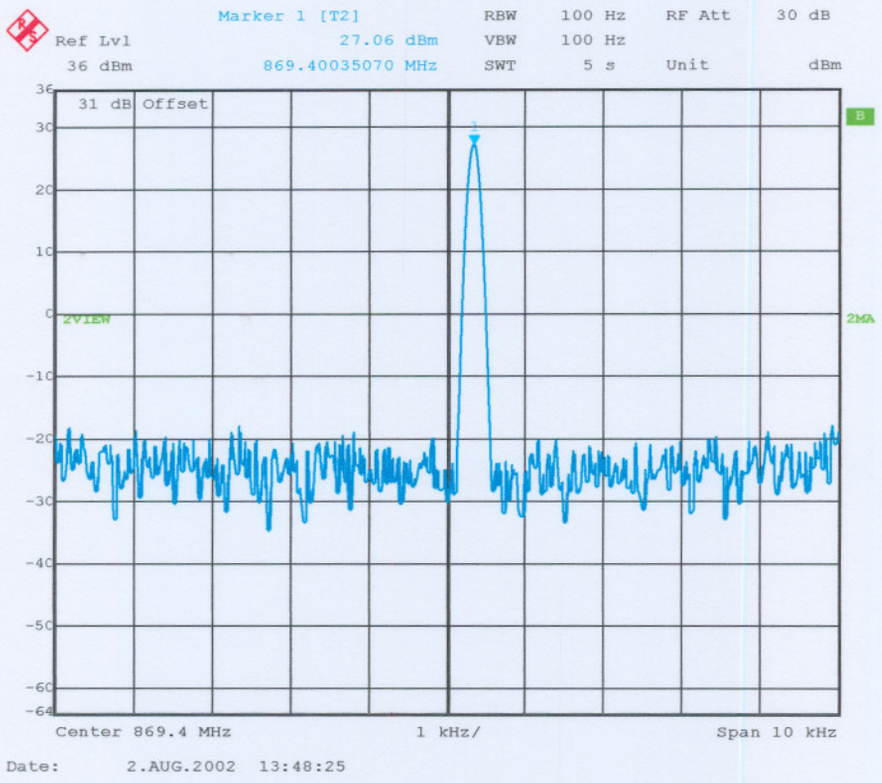

Figure 11: Reader spectrum for the iP-X 64kbit/s TTO protocol.

The iP-X backscatter spectrum is shown in Figure 12 below. This spectrum was measured at the tag with a 10 dB coupler. In practice the backscatter signal is very weak (< -60 dBc at 1 m). The central spur is the carrier at 869.4 MHz. The data spectrum starts at approximately 32 kHz with a peak at 64 kHz (the baud rate) and at 128 kHz (caused by the ¼ bit pulses of the pulse position encoding). The data spectrum is then repeated at the third harmonic of 64 kHz. It is clear that a high pass filter with a cut-off below 32 kHz can be used to remove the carrier and Doppler components.

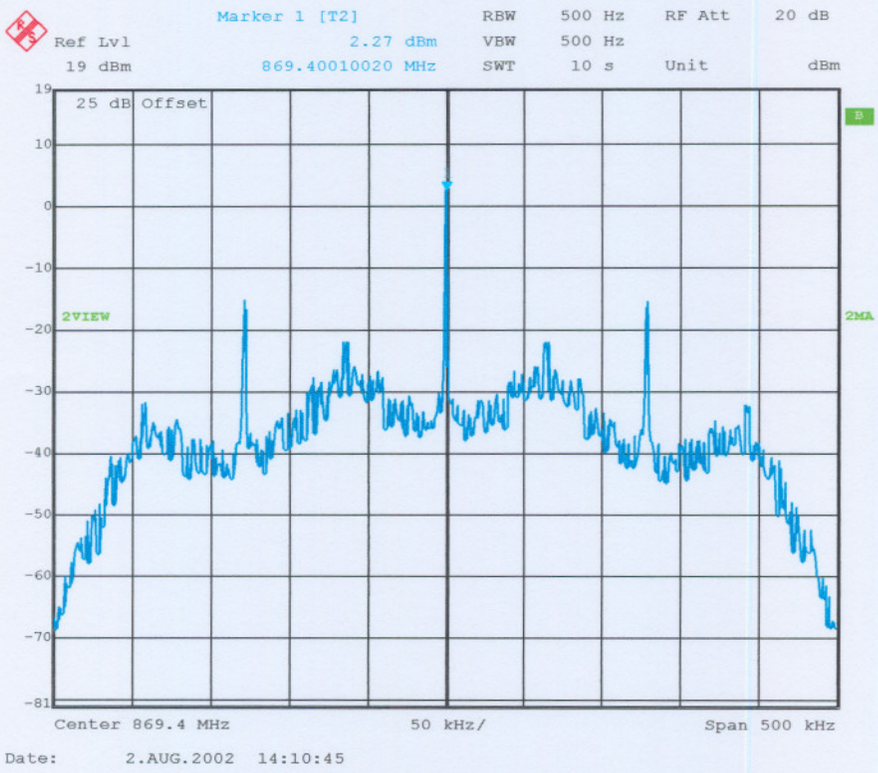

Figure 12: Backscatter spectrum for the iP-X read-only 64kbit/s TTO protocol.

Spectra for various RTF systems are shown in Figure 13 to Figure 15. As can be seen, there is little or no separation between carrier and data, making it difficult to remove the carrier and Doppler components. As can be seen in Figure 13 the Matrics reader spectrum is also extremely wide band.

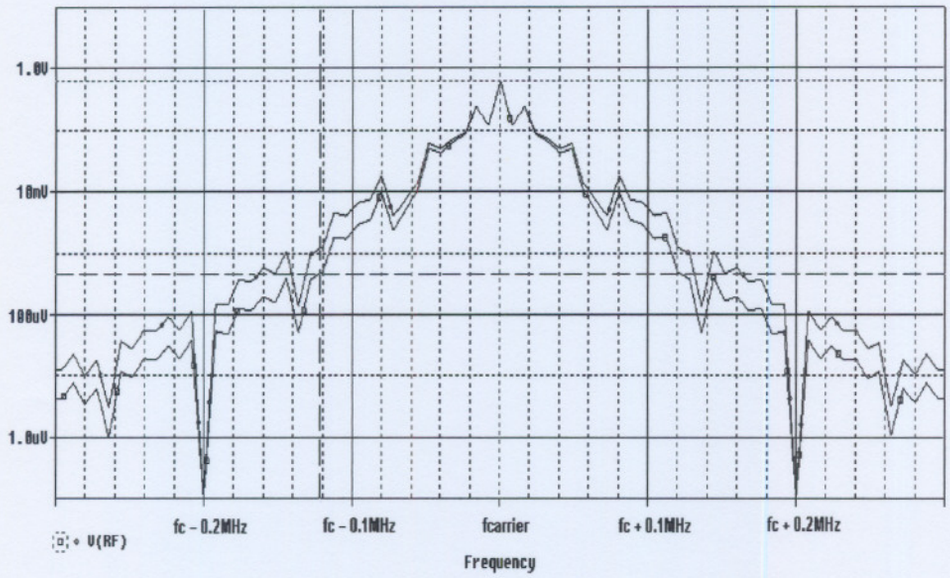

Figure 13: Typical RTF forward link (reader) spectrum (Courtesy Matrics)

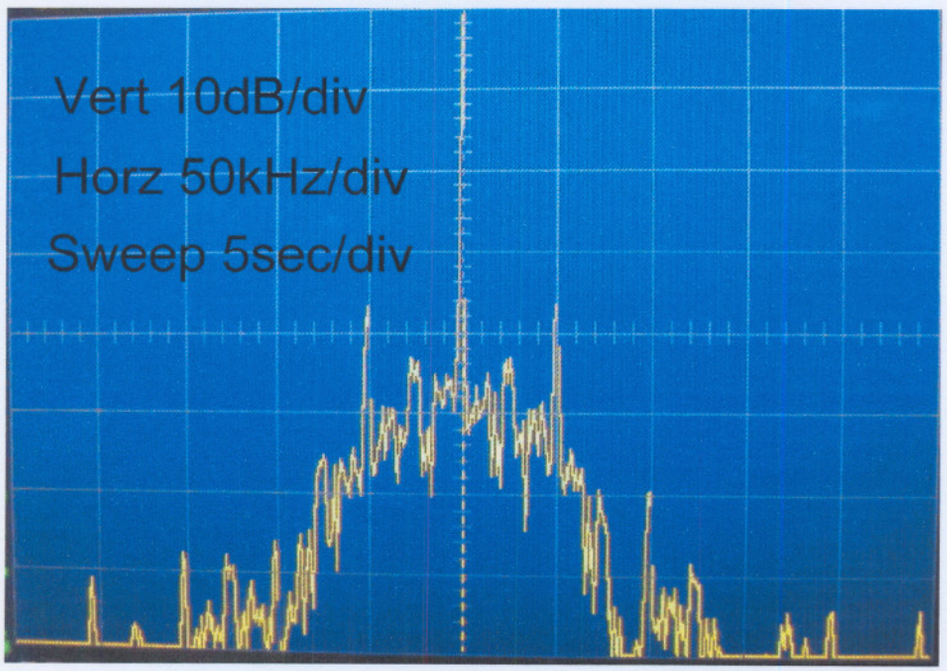

Figure 14: Transmitter Spectrum ISO 18000-6 Type A, ETSI 30% modulation.

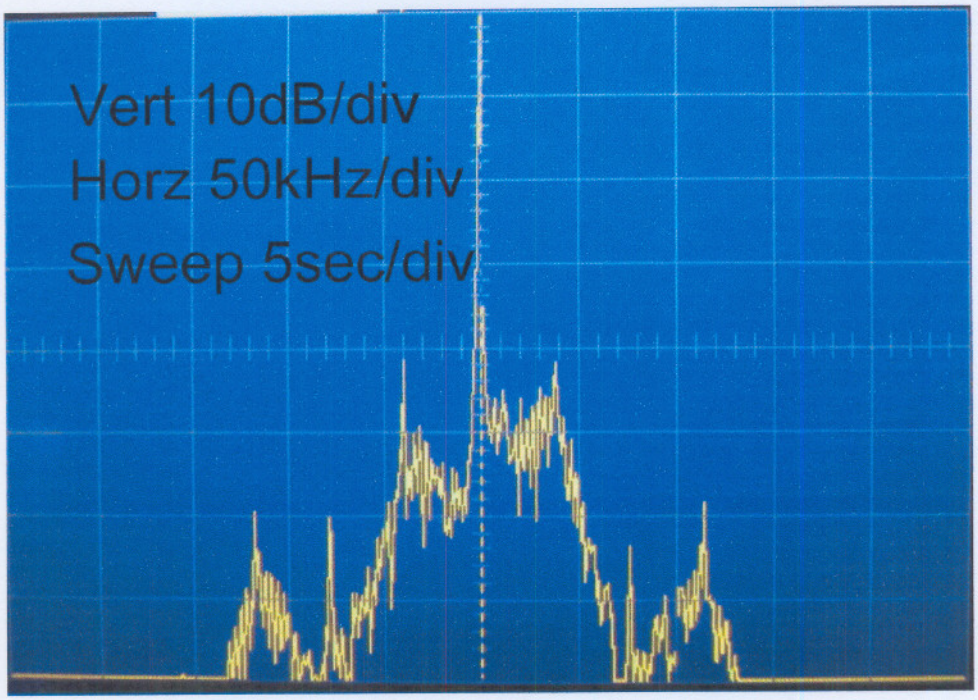

Figure 15: Transmitter Spectrum ISO 18000-6 Type B, ETSI 11% modulation.

From the spectral analysis above, it is readily seen that read-only TTO readers can be operated at a single frequency in close proximity. *This is an extremely favourable characteristic of the protocol developed in this work.* The main reason for this ability is that, at high baud rates, the data spectrum is sufficiently far away from the carrier to make it possible to filter out difference components and inter-modulation products from other reader carriers in the vicinity. This interference can be suppressed with a high-pass or band-pass filter. A 64 kbit/s tag has spectral components down to 32 kHz. The readers are specified to be within 1 kHz of each other. In practice the carrier of a reader will also drift with temperature. The iP-X readers use 5 ppm temperature stabilised synthesizers. This means that the maximum frequency difference be any two readers will be less than 6 kHz, giving a

maximum Doppler frequency of 6 kHz. As a result a filter between 6 kHz and 32 kHz will remove the carrier and difference components effectively.

Assuming a reader separation of 10 m, the strength of the spurious Doppler is -14 dBm in the USA and -22 dBm in Europe. The backscatter strengths at maximum range in both cases are –74 dBm and –67 dBm respectively. The filter is therefore defined: We need at least 60 dB of suppression in the USA and 45 dB suppression in Europe at 6 kHz.

In the case of RTF readers or TTF readers where the reader spectrum overlaps the tag spectrum, spurious reader spectral components cannot easily be filtered out. *This is a significant drawback of such protocols.* RTF and TTF derived systems cannot easily co-exist with other readers in the same channel and will have at least 45 dB higher levels of interference, compared with TTO systems. With 6dB of path loss for every doubling in distance, this implies that TTO readers can potentially be placed 200 times closer together than other readers.

Frequency hopping and frequency agility is proposed in ISO18000-6 to counter the above problem. Unfortunately such measures increase the reader complexity and only solve part of the problem. Tags typically have quite large bandwidths (as much as 50 MHz to 100 MHz) and will detect commands from readers in all the channels.

3.8.5. Analysis of minimum separation distances

Reader interference affects total throughput by limiting the minimum separation distance between readers, thereby limiting the total number of readers that can be deployed at one site. In order to demonstrate the magnitude of this problem, the minimum separation distance will now be calculated.

The analysis that follows is purely theoretical but proves the hypothesis that reader interference is a severe limiting factor. One must bear in mind, though, that practical constraints on the reader technology such as reader front-end saturation, RF *leakage, and*

other non-linear effects may impose different constraints on reader spacing, but this is a reader design issue and does not fall within the scope of this work.

As we have seen in paragraph 3.7.2 the minimum separation distance between two readers can be as little as 1.5 m if only dynamic range considerations are taken into account. In the following analysis the required separation distance between readers is investigated for cases where readers may interfere, either with other tag to reader communications, or with the backscatter from tags to reader. The second case (and more severe case, as will be shown below) would be likely in cases where the reader transmission spectrum overlaps the tag backscatter spectrum, that is, typically where RTF and binary search protocols are used.

Consider the scenario depicted in Figure 16 below:

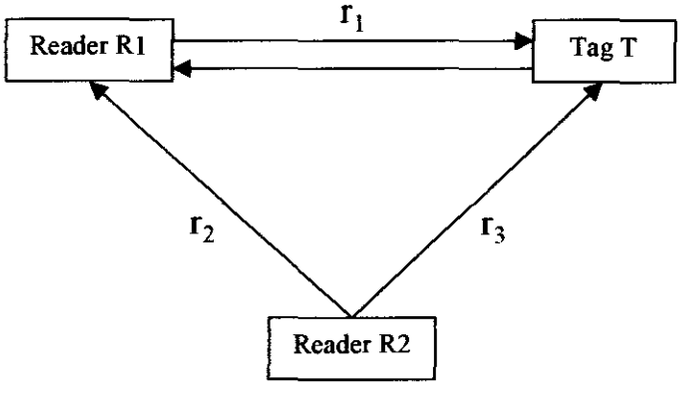

Figure 16: Interference scenario.

Reader R1 attempts to communicate with Tag T. Reader R2 is polling for tags or communicating with tags in its own vicinity.

For R2 not to interfere with the communication from R1 to T, its signal must be at least smaller than R1's signal at T. Actually, depending on Tag T's threshold settings the voltage as a result of R2 (V_{R2}) should probably be less than half the voltage as a result of R1 (V_{R1}).

For the purpose of the following calculations we will assume omni-directional antennas on both tag and readers. Directional antennas can make matters better or worse, depending on the actual system layout and the level of reflections off nearby objects. We will also assume that both readers transmit at the same power level and modulation index.

In the analysis below, the following naming conventions will be used:

V_{R1}, P_{R1} is the signal voltage and power at T caused by R1
V_{R2}, P_{R2} is the signal voltage and power at T caused by R2

At Tag T:

$$V_{R1} > 2V_{R2} \qquad \text{- (14)}$$

$$P_{R1} \propto \frac{1}{r_1^2} \Rightarrow V_{R1} \propto \frac{1}{r_1} \qquad \text{- (15)}$$

Similarly:

$$V_{R2} \propto \frac{1}{r_3} \qquad \text{- (16)}$$

From (14):

$$r_3 > 2r_1 \qquad \text{- (17)}$$

Power varies proportionally to the inverse square of the distance, but voltage varies proportionally to just the inverse of the distance. r_3/r_1 will always have to be more than the ratio of signal strengths that the tag can reliably discern.

However, the more serious interference occurs at Reader R1, where the signal from R2 interferes with the backscatter from Tag T. The backscatter signal

power obeys the Radar law and varies proportionally to the inverse fourth power of the distance, while the interfering signal power from R2 only varies proportionally to the inverse square of the distance. In addition, the strength of the backscatter signal is affected by the RCS of the tag. The tag is not a perfect reflector and only a portion of the incident radiation is reflected.

In the analysis below, the following naming conventions will be used:

V_T is the signal voltage at R1 as a result of the backscatter from T
V_{R2} is the signal voltage at R1 as a result of transmissions by R2
P_T I is the signal power at R1 as a result of the backscatter from T
P_{R2} is the signal power at R1 as a result of transmissions by R2
P_2 is the signal power transmitted by R2
G_1 is the gain of R1
G_2 is the gain of R2

In order to successfully receive data from the tag, the received voltage at Reader R1 should typically be double that of the voltage resulting from interference from Reader 2:

$$V_T > 2V_{R2} \qquad \text{- (18)}$$

$$\Rightarrow P_T > 4P_{R2} \qquad \text{- (19)}$$

The received power at R1 as a result of R2 is given by:

$$P_{R2} = \frac{P_2 G_2 A_{e1}}{4\pi r_2^2} \qquad \text{- (20)}$$

Since the effective capture area of an antenna is given by:

$$A_{e1} = \frac{\lambda^2}{4\pi} G_1 \qquad \text{- (21)}$$

it follows that:

$$\Rightarrow P_{R2} = \frac{P_2 G_2 G_1 \lambda^2}{(4\pi r_2)^2} \qquad \text{- (22)}$$

From the radar equation:

$$P_T = \frac{P_1 G_1^2 \lambda^2 \sigma}{(4\pi)^3 r_1^4} \qquad \text{- (23)}$$

where σ = RCS (Radar Cross Section).

Combining (19), (22) and (23) gives:

$$\frac{P_1 G_1^2 \lambda^2 \sigma}{(4\pi)^3 r_1^4} > 4 \frac{P_2 G_2 G_1 \lambda^2}{(4\pi r_2)^2} \qquad \text{- (24)}$$

With $G_1 = G_2$, $P_1 = P_2$ and simplifying (24) gives:

$$\frac{\sigma}{4\pi r_1^4} > \frac{4}{r_2^2} \qquad \text{- (25)}$$

and solving for r_2 gives:

$$r_2 > 4 \cdot \sqrt{\frac{\pi}{\sigma}} \cdot r_1^2 \qquad \text{- (26)}$$

With $\sigma \approx 10$ cm^2 for a typical tag (Matrics)

$$r_2 > 71 r_1^2 \qquad \text{- (27)}$$

This implies that non-TTO readers with reading ranges of 3 m (typical European performance) will have to be spaced by 639 m in order to avoid the possibility of interference, while readers with reading ranges in excess of 10 m will have to be spaced by at least 7.1 km.

The above analysis is valid for omni-directional antennas, or for the special case where directional antennas point directly at each other. The use of directional reader antennas can improve matters, depending on the actual

system layout and the level of reflections off nearby objects. In addition, low modulation indexes may also improve matters. A 10% modulation index will effectively mean that the energy in the reader modulation is 100 times lower, which reduces the required separation by a factor 10.

3.9. Multi-path propagation

One of the major problems experienced in UHF RFID applications, is the effect of multi-path propagation on system perfromance. In TV systems multi-path propagation creates ghosts on the screen and in radio and cell phone systems, multi-path propagation causes fading. *In RFID systems, multi-path propagation causes nulls in the energy field, resulting in areas where tags cannot be powered up.* In addition, the backscatter is also subject to fading.

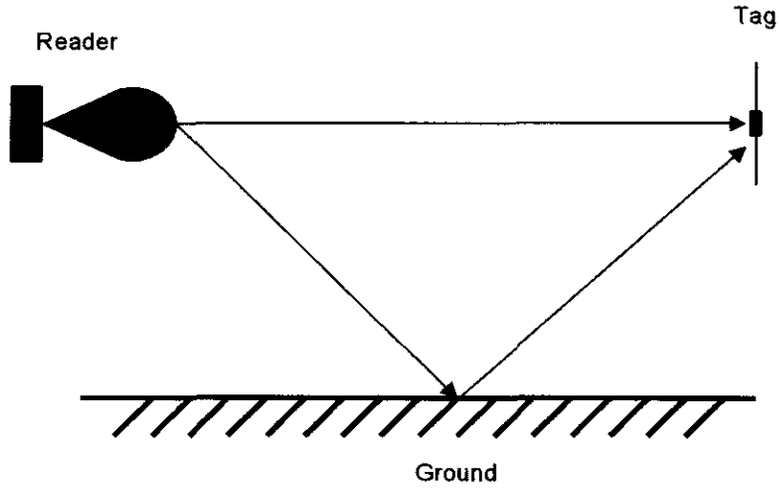

Figure 17: Multi-path propagation.

Refer to Figure 17 above. An air wave travels directly from the reader to the tag. At the same time, a reflection from the ground also reaches the tag, referred to as a ground wave. The ground wave has a longer path to travel than the air wave. When the difference in path lengths is equal to a multiple of the wavelength ($\Delta d = n\lambda$), the two waves add constructively at the tag,

resulting in a local increase or peak in the power density. When the path length difference is equal to a multiple of the wavelength plus half a wavelength ($\Delta d = n\lambda + \frac{\lambda}{2}$) the two waves add destructively, thereby causing a local decrease in the energy density or null in the energy field. The same argument applies to the backscatter signal: A tag may be powered-up, but the reader may nevertheless not successfully read it.

Figure 18 and Figure 19 below show examples of the resulting energy field under ideal conditions. In practice, a simplistic set-up is never encountered. Reflections from obstructions, the objects on which the tags are mounted and even the tags themselves result in more complex fields.

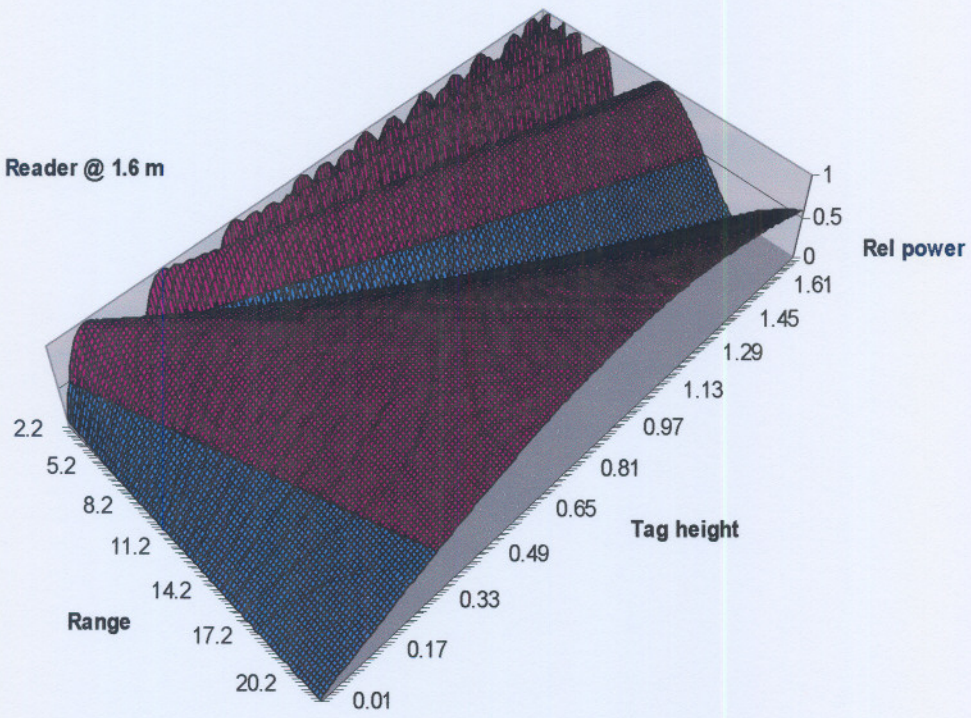

Figure 18: Energy field as a result of multi-path propagation (infinite perfect reflecting ground plane, reader mounted at 1.6 m above the ground plane).

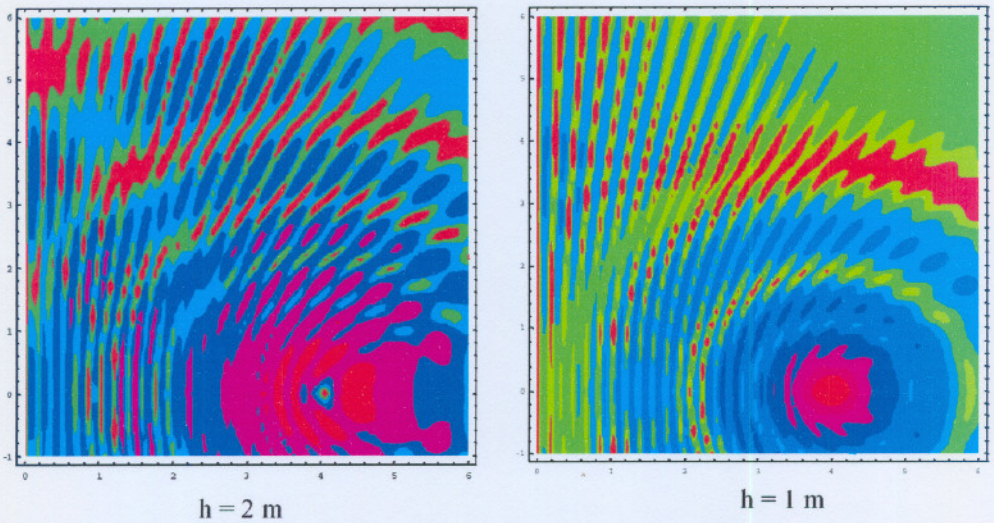

Figure 19: Examples of horizontal power distribution around a reader at two different heights (Palomar [67]).

The final result is that stationary tags cannot always be read as they might be positioned in a null (power or backscatter null). Moving tags will move through nulls and peaks, which will increase the probability of successful reads. The peaks actually increase the potential reading distance. *The main challenge facing the* RFID ***system designer*** *is to design the application so that the tags will be guaranteed to move through peaks, or at least avoid nulls.* As can be seen from the above figures, tags moving towards or away from a single reader are almost guaranteed to move through peaks, while it is possible for a tag that moves across a reader to stay in a null channel.

As a tag moves past a reader through nulls and peaks, it could power up and down all the time. A large storage capacitor could solve this problem, but increases the cost and thickness of a tag. An anti-collision protocol has to survive this powering up and down at short intervals. Protocols that depend on shutting down tags to reduce congestion typically fail or operate at reduced efficiencies as tags are continually being reset. Using non-volatile storage to remember the shutdown state is dangerous, as the tag might stay in this shutdown mode permanently or until it next receives some form of wake-up

command. To counter this problem, all communications can be started with a wake-up command, but this could largely cancel out the advantages of the shutdown function.

An additional factor to consider is that the time a tag spends in a peak could be very short, depending on the speed at which the tag moves. All data exchanges between tag and reader must be kept as short as possible. Protocols that depend on long bi-directional communications sequences to resolve multiple tags e.g. binary search algorithms, could suffer loss of efficiency or limit the speed at which tags may move.

Even without multi-path propagation, i.e. in a continuous field without nulls and peaks, the backscatter signal changes phase every $\frac{\lambda}{4}$ distance (~ 7.5 cm) that a tag moves away from or towards the reader. Consider a point where the backscatter signal arrives in phase with the transmitted carrier. It adds constructively and the reader sees an AM signal. Should the tag now move through a distance of $\frac{\lambda}{4}$ away from or towards the reader, the total path from reader to tag and back will have changed by $\frac{\lambda}{2}$ and the backscatter signal will now arrive out of phase with the transmitted carrier, resulting in destructive addition. The result is still an AM signal, but the phase has changed through 180°. Halfway in-between the reader will actually not see an AM signal but a phase modulated signal. To successfully transmit data from the tag to the reader, the transmission has to take place in less time than it takes the tag to travel $\frac{\lambda}{8}$ in distance, or about 4 cm. An ID transmission in the iP-X protocol takes about 1 ms at 64 kbit/s and 250 µs at 256 kbit/s. These translate to speeds of 40 m/s (144 km/h) and 160 m/s (576 km/h) respectively.

Some techniques have been proposed to *alleviate the multi-path propagation problem, such as sweeping the carrier frequency or frequency hopping.* Unfortunately the bandwidths allowed by regulators are not enough to cancel nulls.

Another solution to multi-path nulls is to make use of multiple readers or add slave antennas to readers. The main problem with this approach is that static or slowly changing interference patterns are created that can actually accentuate the problem, creating for example null paths so that tags can move right past the readers while staying in a null all the way.

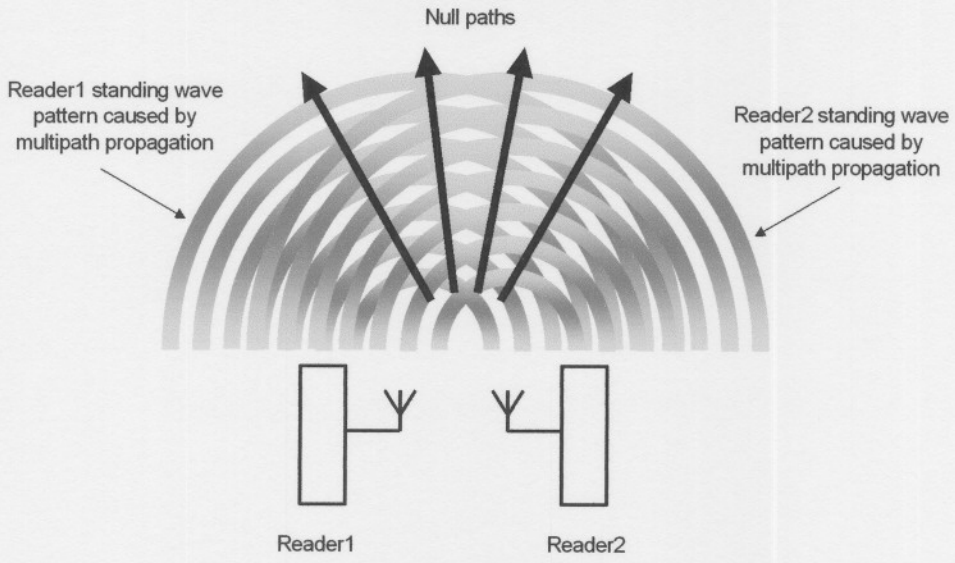

Figure 20: Null paths as a result of interference between two standing wave patterns.

The *only workable solution to multi-path nulls* that we have found is to multiplex between two or more readers, using what is known as *spatial diversity.* This can normally alleviate the problem of nulls, as the field pattern will change as the readers are multiplexed. However, this limits the speed at which tags can move past the readers.

3.10. Tag RF design aspects

3.10.1. Antenna matching

Tag antennas design is a science and an art of its own and is not understood really well. *Detail design of antennas for practical RFID systems is not a requirement for this thesis, but is nevertheless treated as part of the discussion for the sake of completeness.*

The RFID chip does not present a constant impedance to the antenna. Instead the impedance varies as the tag powers up and modulates the antenna. As is usually the case with ongoing development, research is still being done to determine the correct design approach regarding the impedance matching between antenna and tag. Theoretical support still lacks for selecting between a high antenna impedance for maximum voltage transfer, match to chip for maximum energy transfer, or low antenna impedance for maximum current transfer during power-up. Empirical tests at iPico indicate that a good impedance match based on power transfer is a good compromise. This was found by systematically adjusting a dipole antenna length for maximum reading range, and then measuring the dipole impedance to determine the optimum matching impedance.

Currently all the iP-X tag antennas are dipoles or variations of folded dipoles. These antennas can be easily trimmed to match almost any configuration of folding or dielectric substrate material.

3.10.2. Bandwidth

One of the design aims for a tag antenna is that it should ideally cover both the European and USA bands, i.e. 860 – 930 MHz, so that transatlantic shipments can be read on both sides of the ocean. Fractal antennas [57],[58], [59],[60] promise to achieve this, but currently at unacceptably high costs. High bandwidth antennas are also less susceptible to influences from substrate dielectric characteristics.

The iP-X dipole antennas have bandwidths in the order of 50 MHz and do not quite cover the full range. A tag that is optimised for Europe will, however, perform reasonably well in the USA, because of the much higher reader transmitted power allowed there.

3.10.3. Gain

There is a perception that a tag should have an omni-directional antenna, i.e. have an antenna with a gain of 1 (0 dBi). This is primarily so that tags can be read in all orientations, especially when mounted on objects in applications where the tag orientation cannot be guaranteed, such as in parcel shipping and grocery stores. Omni-directional antennas, especially planar ones, are difficult to design and quite often costly to manufacture, requiring more than one conductor layer. Matrics achieves a level of omni-directionality by having two antenna ports on their chip and multiplexing between two orthogonal dipole antennas.

Unfortunately the tag antenna radiation pattern is almost always modified by the object on which it is mounted and omni-directionality is consequently lost. Instead of trying to achieve omni-directionality with the tag antenna, two circularly polarised readers can be used to achieve the same effect. A dipole antenna can be read in all orientations in the plane parallel to the reader with circularly polarised antennas. By using two orthogonal readers, the third dimension is also covered.

When the tags are mounted on a pallet, re-usable container or vehicle, the orientation of the tag can quite often be controlled. By giving the tag antenna gain, the reading range can be increased. Note, however, that as the tag moves past a reader, the angle to the reader changes continually. Higher gain antennas will be more susceptible to displacements sideways away from the reader, and when moving at speed will spend a shorter time in an acceptable orientation to the reader.

3.10.4. Substrate dielectric characteristics

The dielectric constant of the substrate base material on which the tags are mounted or etched affects the speed of propagation of the electromagnetic wave in the antenna, and consequently the centre frequency of the antenna. This is particularly a problem with label tags that can be stuck on any

background material. Highly tuned antennas are more likely to be severely affected. Tags that are packaged in a secondary enclosure can be tuned for the dielectric constant of the enclosure material. High dielectric constant materials can also be used to reduce the size of the tag by shortening the antennas.

3.10.5. Reflectors

One easy way of increasing the reading range of a tag is to place a reflector behind it, similar to the reflector used in Yagi TV antennas [49],[55]. Reading range can be nearly doubled. The reflector also shields the tag from the absorbing or reflecting qualities of the material or goods behind the tag, giving a controlled performance under all circumstances.

Such a tag with reflector is typically 15 – 20 mm thick. In applications where it is desirable to have a low profile tag, a material with high dielectric constant can be used between the tag antenna and reflector [54].

3.10.6. Tags in close proximity

There are some applications, e.g. labelling of documents, where it is necessary to use tags in very close proximity. A UHF tag with a dipole antenna has an effective capture area in the order of 140 cm^2 (about 12 cm x 12 cm). When a second tag's effective capture area overlaps with a first tag's capture area, the available energy must be shared between the two tags. When the two capture areas overlap completely each tag has half the energy available to it, resulting in a theoretical 70% reading range reduction. However, in practice the two antennas will detune each other and affect the impedance match, so that both tags will capture much less of the incident energy.

It is also often seen that with two tags in close proximity, one tag can be read, while the second cannot be read at all. This can be explained in terms of diffraction and multi-path propagation. One of the two tags ends up

positioned in a null caused by the other tag's distortion of the energy field and cannot be powered up.

When both tags in close proximity do get powered up, another effect can come into play: Modulation by one tag can reset the second tag or interfere with its anti-collision protocol. Some versions of the Supertag protocol are especially susceptible here. *Modulation by one tag can result in spurious acknowledgements or shutdown commands at the second tag. The iP-X protocols are immune to this kind of interference.*

Brady *et al* have patented a method whereby the tags can be placed on densely space media, such as envelopes [53]. The problems associated with tags in close proximity are solved through spatial diversity, i.e. each tag is positioned differently on the media. This method is not suitable to automatic labelling and does not guarantee that tags in similar positions do not end up in proximity.

3.11. Conclusion

In this chapter we investigated the limitations imposed by the regulatory environment on UHF RFID systems. We studied the implications of the choice of air protocol on the RF performance, which was followed up by a development of the RF design requirements for such a system. A theoretical analysis of the interference between readers and tags was performed, showing that, unless carefully managed, such interference will limit the user's ability to deploy large numbers of readers in close proximity - thereby limiting the total achievable throughput. The iP-X protocol results in a much narrower and cleaner reader transmission spectrum, making it possible to filter reader interference from tag data. This makes it possible to have co-channel, co-located readers.

4. ANTI-COLLISION PROTOCOLS

4.1. Summary

In order to be successful, an anti-collision protocol must be capable of reading large numbers of fast-moving tags with a high probability of success. This chapter analyses anti-collision protocols with emphasis on the Aloha-type TTF protocols, i.e. the Free-running protocol and the Supertag protocol and its derivatives. Finally the iP-X protocol is discussed in depth, using results obtained from the iP-X simulator.

The iP-X protocol is difficult to evaluate analytically due to its stochastic nature. Instead of evaluating the protocol analytically, a simulator was written and used to predict its performance in various scenarios. Such a simulator is a valuable tool in demonstrating the feasibility of the protocol, optimising the design of tag chips that implement the protocol and in design and evaluating system implementations. The accuracy of the simulator developed in this work was verified with actual measurement results.

4.2. Introduction

Historically short-range RFID tags, typically operating at 125 kHz or 13.56 MHz, did not require anti-collision protocols, as only one tag was read at a time. These were also typically "Tag Talks First" (TTF) protocols, i.e. the tags only transmitted their IDs, either once or continuously, when they detected a reader beam. With long-range UHF tags it is possible to fit several tagged items into a reader beam. In order to successfully read tags that are present simultaneously in a reader beam, an anti-collision protocol between tags and reader (multi-read) is required. This is a multi-access problem where tags compete for the communication medium and some arbitration process is required so that all the tags can be reliably identified. Important measures of performance include the time to read a certain number of tags, the confidence

level that all tags have been read, the number of tags at which the channel becomes saturated and the speed at which tags can move past a reader.

The IFF ("Identify Friend or Foe") systems, which are considered to be the first use of electronic identification, use spatial diversity to distinguish between more than one transponder. The radar can separate IFF transponders in azimuth, elevation and distance. Some RFID systems also use spatial diversity, specifically using either the strength of the backscatter reply or a measure of the excitation level of the tag (TEL) as a means to arbitrate between tags.

A second technique for discriminating between multiple transponders is that of frequency diversity, i.e. each tag is assigned a frequency channel to operate in. Unfortunately bandwidth regulations preclude the use of this technique for RFID tags.

The most often used method for discriminating between multiple transponders is that of Time Domain Multiplexing (TDM). Here tags transmit their ID at different times, either randomly (Aloha based protocols) or as instructed by the reader (Binary search algorithms).

The Aloha principle used widely in Ethernet systems is one of the best-known techniques used for arbitration amongst multiple contenders for a communications channel. In this case, when a transmitter attempts a transmission, it also listens. If it detects a collision, it waits a random time before trying again ("Random back-off and wait").

The iP-X and Supertag protocols find their origin in the Aloha technique, with the main difference being that a tag cannot listen to detect a collision. It typically always retries after a random back-off time. The reader has to detect and discard collisions. This technique was developed almost simultaneously at the CSIR [112] and at ISD [27] during 1991. The protocol is a TTF one, i.e. tags transmit without any prompting by the reader. Its main drawback is

saturation. The iP-X protocol [1],[2] reduces this effect. The Supertag variations [28],[31],[32],[33],[34],[35],[36],[37] attempt to speed up the basic protocol by selectively muting or switching off tags.

The "Slotted Aloha or "Framed Aloha" apparently developed by Gemplus but also used by Philips [63] and the Singapore Transit Authority [139] is a variation where tag transmissions are confined to slots controlled by the reader. This converts the protocol from a TTF to an RTF ("Reader Talks First") protocol. This protocol is also used for ISO 1800-6 Type A [86].

The binary search protocols also find their origins in computer networks. They do not suffer from channel saturation as much as the Aloha protocols. The time to read a large number of tags does not start to increase dramatically at some point as the tag numbers increase, but rather stay linear or at worst increases proportionally to Nlog(N), where N is the number of tags. In theory they seem much faster than the Aloha protocols. In practice, mainly due to the low bit rate at which commands can be sent to the tags and due to the inherent non-determinism of RFID environments, these protocols do not achieve higher reading rates.

4.3. Standardisation

Users like standards as they give rise to interoperability and multi-sourcing. Standards are typically not required for niche applications or closed loop applications. Standards sometimes arise out of a coordinated effort, but more often a de facto standard is first created when a proprietary product is widely accepted and used, forcing other suppliers to become compatible, e.g. the HP-IB bus standard that was later accepted as an IEEE standard. Standards do not have to be the best technology, but must be good enough. Marketing also plays an important role.

The ubiquitous bar code was developed during the 1970's as the first attempt to standardise electronic identification. It eventually proliferated into

approximately 39 standards. Similarly the 13.56 MHz RFID standard proliferated into at least six different standards. Bar codes took many years to be accepted as a standard and it has only been during the last few years that most supermarkets and even smaller stores converted to bar code checkout. It is expected that an RFID standard will be accepted faster, as companies have already realised the potential benefits of supply chain visibility and control that could result. Unfortunately there is currently no clear candidate for a standard, as the current products that have been proposed for a standard seem to perform inadequately. In addition, vested interests have already started to lead to proliferation, as is seen in the current ISO 18000-6 proposals. There is a very real possibility that the iP-X product and protocol could become a de facto standard if it is accepted widely.

4.3.1. Bar codes

Since the first scan in 1973 the Uniform Product Code (UPC) grew to include a European variant the EAN/UCC-13, a Japanese Article Numbering Code (JAN), the Shipping Container Code (SCC-14), and many others. The various codes are now included in a superset, the Global Trade Item Number (GTIN). The GTIN is managed by the Uniform Code Council (UCC) and the European Article Numbering International (EAN). Over 80 000 companies in 90 countries today use the UCC/EAN numbering system.

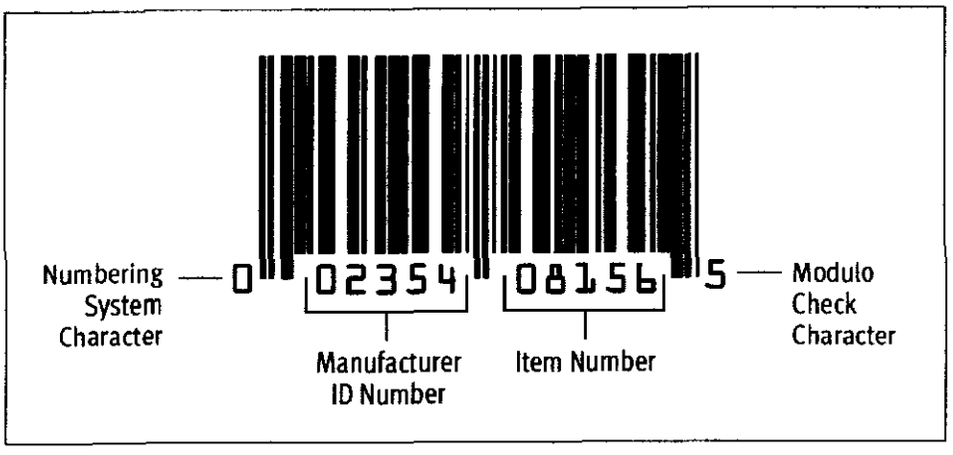

Figure 21: Universal Product Code (UPC) (Courtesy Auto-ID Center)

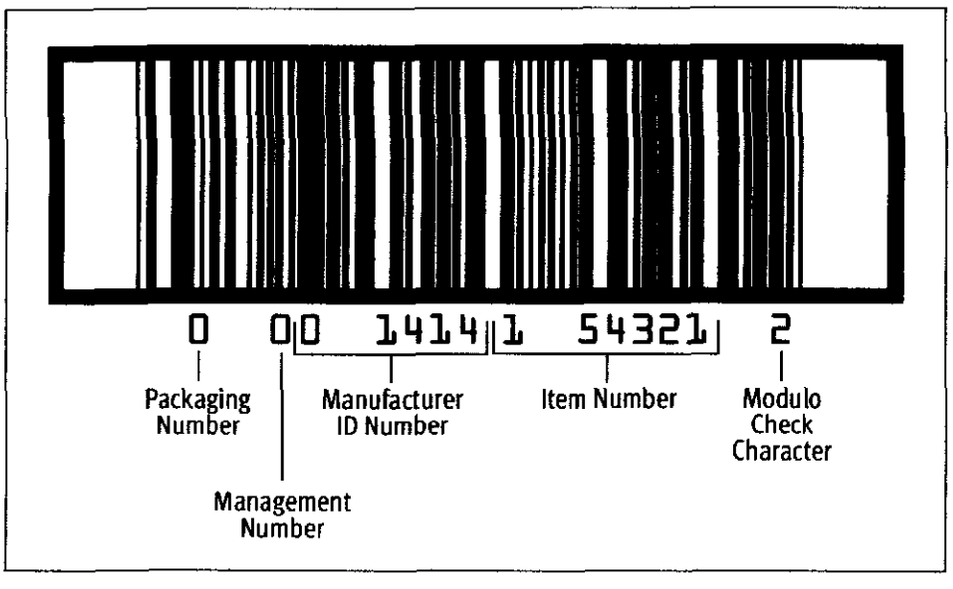

Figure 22: Shipping Container Code (EAN/UCC-14) (Courtesy Auto-ID Center)

4.3.2. UCC/EAN GTAG

More or less in 2000 UCC/EAN decided to try and repeat their success with bar code standardisation in the field of RFID. They formed a committee out of prominent players in industry (Intermec, BTG, Bistar, Samsys, SCS, Gemplus, Texas Instruments, Philips and others), set down a minimum

standard and invited proposals for a GTAG (Global Tag). They argued that the only electronic identification technology with suitable performance for the supply chain was UHF RFID. They started to lobby EC for more power and spectrum, arguing that sufficient reading range could not be achieved under current EC regulations, and that European logistics companies would find themselves at a disadvantage compared with American companies. The GTAG committee insisted that GTAG must be an RTF technology, which left no place for the iP-X protocol. It is interesting to note that the iP-X product does in fact meet all of their objectives in Europe, even under current regulations.

Their effort created an awareness and acceptance for UHF RFID, e.g. Chep announced that they would use GTAG UHF RFID to track and manage their 300 million pallets worldwide. Unfortunately a big pilot based on technology from Intermec, one of the major players in GTAG, failed.

4.3.3. Palomar

The Palomar project is a European Commission funded project to create an RFID system that would perform well under the strict European spectrum regulations. A number of European companies participated, namely Atmel (Germany and France), Rafsec and Idesco. They achieved their primary objectives of good reading range at 500 mW erp reader power and reported that they could power a tag at -12 dBm (compared to the 0 or -1 dBm of RF power for iP-X tags). The Palomar over-the-air protocol was eventually submitted as a candidate for an ISO standard [86].

4.3.4. ISO

The GTAG standardisation process was eventually converted into an ISO process and GTAG became one of the inputs to the ISO standard, together with submissions from companies such as Matrics and Palomar. Vested interests prevented consensus and they eventually settled for two protocols in the standard - Type A based on GTAG (slotted Aloha) and supported by

BTG, Samsys, Bistar, Gemplus, and Type B based on the Intermec protocol and supported by Intermec and Philips. A successful artefact demonstration, using a P4022 as the RF front-end, was done in Orlando in January 2003 and a final specification was expected towards the middle of 2003[2].

4.3.5. Auto-ID and EPC

The Massachusetts Institute of Technology (MIT) Auto-ID Center has been promoting its own standard in competition with the ISO standard. Their stated aim is to develop a standard that would result in a very low cost tag (towards USD 0.05) [81]. To this end, they have proposed, amongst others, a radical new assembly technique called fluidic assembly. In this method chips are not handled individually by machines or robots, but are rather prepared in a "slurry" and almost screen-printed into specially prepared cavities in the substrate containing printed antenna.

Chip size must be very small (<0.5 mm^2), which implies a read-only protocol, with intelligence and storage moved off the tag and into databases situated anywhere on the Internet. To this end they have proposed a 96 bit Electronic Product Code (EPC), an RFID replacement for the bar code GTIN number [80], as well as a more compact 64 bit EPC [79]. The EPC code contains a pointer to an EPC manager, which will resolve the object class (product code) and contain additional data as required, as well as a serial number.

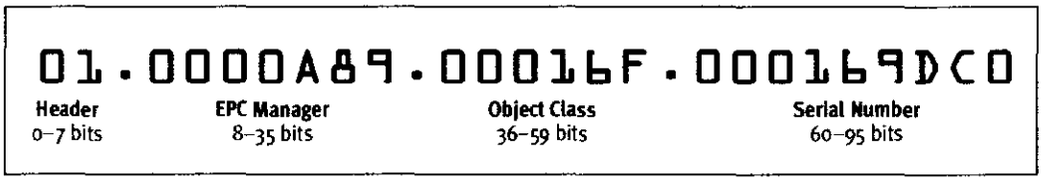

Figure 23: Electronic Product Code (Courtesy MIT).

[2] The EPC process at MIT has in the meantime been taken over by UCC/EAN. They have announced that they would attempt to move closer to ISO. This will probably delay the finalisation of the ISO standard and is most likely to result in a third ISO type.

The Auto-ID Center has managed to win the support of a large number of companies, mainly end-users. The technology is primarily provided by Alien, Matrics and Rafsec.

The EPC numbering scheme is in reality protocol independent. Auto-ID has nevertheless developed their own over-the-air protocol, somewhat to the chagrin of the ISO committee [88].

The EPC scheme does not take cognisance of the strong CRC requirements of RFID due to the low signal-to-noise ratio. The 96 bit EPC will in practice have to have an additional 32 bit for a CRC, while the 64 bit EPC will have to be stretched to possibly 80 bits.

iP-X can support EPC in various ways [159]:

- Virtual EPC

The unique ID is translated to a virtual EPC by means of a look-up table in the reader.

- EPC in R/W memory

The iP-X4 R/W chip can support a full EPC code in its memory. After a tag has been uniquely identified through the anti-collision sequence, the EPC can be read.

- Native EPC

It is planned that the iP-X5 chip will have a native EPC mode where a 128 bit EPC will be transmitted during the anti-collision sequence.

- iP-X EPC

One of the strong features of the iP-X protocol is its reliance on factory-programmed unique ID numbers. Because the ID numbers are not field-programmable, they are relatively secure and difficult to counterfeit. The ID can be used for authentication, a growing requirement of brand owners facing competition and losses from grey manufacturers. EPC, by its nature, is a field-programmed number, typically applied by the manufacturer or packaging house. In our proposed solution the EPC number consists of two 64-bit numbers. The first contains a factory-programmed unique ID, exactly like the 64 bit ID of current iP-X chips. This is followed by a 64-bit field-programmable number containing an EPC manager and product code.

4.3.6. Proposed TTF standard

ISO 18000-6, like GTAG before it, attempts to standardise every aspect, from the UHF modulation down to bit flags in the commands. However, what is required urgently is a standard that would allow inter-operability. For RTF tags this means only agreeing on a wake-up standard and wake-up duty cycle. For TTF tags it means only agreeing on a duty cycle. The following has been proposed [7]:

Speed	Number of tags simultaneously in reader beam	Average duty cycle
Slow (< 2 m/s)	>20	< 0.3%
Fast (> 2 m/s)	2 - 20	<1.2%
Very fast (> 16 m/s	2 or less	< 4.8%

Table 2: Proposed duty cycle standard

The iP-X protocol is currently a good candidate for becoming a de facto standard, especially in Europe where it is the only protocol that gives acceptable performance in the limited bandwidth and power.

4.4. Common features of anti-collision protocols

4.4.1. Determinism

One of the distinguishing features between protocols is the level of non-determinism employed. Protocols such as those employed by SCS, Matrics and the MIT binary search

are in theory completely deterministic, i.e. there is a finite upper bound to the time in which the anti-collision terminates. Protocols such as the one used by Intermec and Philips and proposed for ISO18000-6 type B have a level of non-determinism in that slots are chosen randomly or pseudo-randomly. *The iP-X protocol and the basis of the Supertag protocol are completely stochastic, as every transmission time is chosen in a random (actually pseudo-random) manner. In addition, randomness in the oscillator centre frequency is used to further increase the randomness.* Theoretically, there is no upper bound to how long it can take to identify every tag in the reading beam. From a critical perspective, this is one of the main criticisms levelled at the iP-X protocol. Practically, a chosen level of confidence can be reached in finite time, as is shown later in this chapter. In practice, all protocols will suffer from random delays for various reasons. Considering that the whole tag reading process is inherently extremely random – tags entering and leaving the reader beam at random times, and virtually random distribution of peaks and nulls due to multi-path propagation - the randomness in the iP-X protocol is not particularly detrimental.

4.4.2. Switch-off

A switch-off feature (also variously called dormant state, isolation state, sleep state, mute state or cloaking) is commonly used to accelerate the anti-collision protocol by turning off successfully read tags in order to reduce the remaining tag population still to be searched. While it can lead to much faster reading times, it also often leads to higher error rates.

The following are some of the problem areas associated with switch-off:

- The main problem is how and when to terminate the switch-off state. Supertag e.g. terminates the switch-off state at power-on reset. This could mean that the tag never exits from the state or alternatively exits immediately as the tag moves through nulls in the field, thereby largely offsetting the acceleration gains. Bistar used a flag to indicate a switched-off state, but this flag had a time-constant varying from a

few seconds to a few hours, depending on process quality, leakage currents and temperature [143]. SCS use a "wake-up" command to terminate the switched-off state. As there is no guarantee that tags entering a reading beam had been successfully woken-up previously, the anti-collision cycle has to start with a wake-up command. This command has to be transmitted at regular intervals to ensure that new arrivals are woken up. This could mean that tags that have already been successfully read are also woken up again, thereby once again affecting the acceleration factor negatively.

- Tags are only read once. This is often held up as an advantage, because it reduces the bandwidth required between the reader and the information system behind it. The bandwidth problem is easily solved by filtering the data in the reader. The main drawback is that no information can be extracted about the quality of the reading process, other than the number of tags that were missed. One cannot deduce for example how long the tags spent in the beam or what the reading rate was.

- The process is typically not re-entrant. Once a tag has been switched off, it cannot easily be read again, for instance a sales transaction at a checkout counter cannot easily be repeated in case of error and tags cannot be read by two different readers in succession to determine direction of movement.

- Two readers cannot be used to detect direction of movement. If the first reader turns off the tags, the second reader cannot read them.

- Spurious switch-off: Especially the Supertag protocols are vulnerable because of the simplicity of their switch-off commands. Noise and interference from other tags can mimic switch-off signals.

- There is no redundancy. If a tag is read once and turned off, there is no chance to read it again, should it turn out that the received ID in fact fails a CRC check or does not exist at all in the data base.

4.4.3. Binary search vs. Stochastic

Proponents of binary search algorithms claim as their main advantages speed and determinism. Especially when the tags are stationary or the binary tree can be pruned, e.g. in the case of a known ID or known block of IDs, binary searches can be very fast. As pointed out in Chapter 3, the RF environment is such that stationary tags cannot always be successfully read. When tags are randomly entering and leaving the reader beam, the whole process becomes non-deterministic, and the repeated binary searches that are then required negate much of the speed advantage.

Scharfeld [77] has compared a binary search protocol to the Supertag protocols. Based on simulations, he found that when tags are distributed serially, the binary search could be very fast, comparable to the Supertag Fast Switch-off version. However, when tags are distributed randomly, the binary tree search is much slower, comparable to the Supertag Switch-off version. His simulations were for static populations and did not take into account the effect of late arrivals and early departures, which would slow the binary search down further.

Binary searches depend on a lot of reader and tag interaction. Reader command bit rates are limited by regulatory imposed bandwidths, so that while the baud rates of e.g. the iP-X protocol can be increased to accelerate the protocol, the same cannot be done for binary search protocols. The end result is that an iP-X protocol running at 256 kbit/s achieves much the same if not better performance than a binary search protocol running at 40 kbit/s or 64 kbit/s.

4.5. Protocols summary

4.5.1. Singapore Transit Authority

Anh *et al* [139] describe a randomised time division multiplexing technique used by the Singapore Transit Authority for automatic vehicle identification. The technique is RTF and similar to framed Aloha. The time between regular interrogation signals is divided into a large number of slots. Each tag selects a slot randomly. The protocol allows for changing the number of slots to reduce collisions during high traffic density.

4.5.2. ISD

Cole *et al* [27] describe an anti-collision protocol used for a low frequency baggage identification system. The protocol is similar to the Free-running protocol. The baggage labels reply intermittently, with the period between replies distributed pseudo-randomly.

4.5.3. MIT Memoryless Protocol

Siu at MIT [76] presents a classical binary search protocol. The reader transmits strings of bits, starting with an empty string. Tags reply with their IDs if the string matches the start of the ID. No reply implies that there are no tags further in this branch of the binary tree and the branch can be pruned. A single ID reply is recorded and the branch is also pruned. When a collision is detected the branch forks and '1' and '0' is appended to create two new strings. The protocol is memoryless, because tags only respond to the current enquiry, and deterministic.

4.5.4. IBM

A patent by Chan *et al* describes a tree-splitting binary search anti-collision protocol [56]. The set of tags present are divided into smaller and smaller subsets, until only one tag remains in a subset. The division into smaller subsets is done by the tags themselves in a random manner.

4.5.5. SCS

Walter *et al* (SCS) [48] has patented a variation on the MIT binary search protocol. Here the reader searches the binary tree bit by bit by commanding tags recursively to respond when they have a '1' in the *n*th bit position. Successful IDs are placed in "isolation" – a sleep or switched-off state from which the tag has to be woken. Unlike the MIT protocol, it is not memoryless – each tag has to remember which bit is currently being interrogated.

4.5.6. Micron

Black *et al* [46] describe an anti-collision protocol, which they claim is suitable for read-only devices. The patent describes the application to a low frequency RFID system where clocks are also transmitted to the tag chip. However, the general principle is applicable to UHF tags as well. The approach is similar to that of Intermec. Each tag calculates a random slot in which to transmit. During transmission of the ID, the reader sends a signal to indicate an error as soon as it detects a collision or other error. In this case the tag generates a new random slot number. If an ID is successfully transmitted, the reader once again indicates this by transmitting a suitable signal to the tags. All the tags that still have to transmit, decrement their slot counters. When the slot counter reaches zero an ID transmission is attempted.

4.5.7. Intermec

Intermec proposed their non-deterministic binary tree search to the ISO committee. The protocol was included as Type B in the ISO 18000-6 standard (See paragraph. 4.5.15).

4.5.8. Philips

The I-Code protocol from Philips is a "framed Aloha" protocol [63]. Tags transmit their IDs in a randomly chosen slot in a frame. The number of slots in the frame is determined by the reader and communicated to the tags. By estimating the total number of tags by looking at the number of collisions, the

frame size can be adjusted to an optimal number of slots. The read process is repeated until the probability of having read all tags has reached a sufficiently high value. The I-Code protocol is mainly used at 13.56 MHz.

4.5.9. Matrics

Matrics performs a bit by bit binary tree traversal [133], in which the reader transmits a '1' or 0' for the current bit position, and tags that have a matching bit respond with their next bit. Tags that do not have a matching bit, go mute until the next traversal. If only one kind of bit is received by the reader (it could be from more than one tag), the other branch of the tree can be pruned. If both '1' and '0' is received, the reader picks one and asks for the next bit, while putting the other option (branch) on a stack to traverse later. Successfully read tags go dormant.

4.5.10. Palomar

As far as is known, Palomar implements a modified binary tree anti-collision scheme, but can apparently also support Aloha based protocols [69],[86].

4.5.11. BTG

The BTG Supertag protocol is an Aloha type non-deterministic protocol. It was developed at the CSIR during the 1990s and then sold to BTG. It is based on a free-running stochastic process – tags transmit their IDs at random times. In order to accelerate the process and to avoid early saturation, tags can be muted to allow one tag to transmit without a collision and switched off after a successful transmission. This protocol is discussed in depth in Par. 4.6

4.5.12. iPico (iP-X)

The iPico iP-X protocol is based on the same free-running algorithm that forms the basis of the Supertag protocols. There are no data transmissions from the reader to the tag in the read-only version of the protocol, resulting in low interference, which allows the deployment of readers in close proximity.

In the R/W version of the protocol, the reader also does not send any commands to tags during the anti-collision phase. Once a tag has been uniquely identified, the necessary Read or Write commands are sent. The iP-X protocol is discussed further in paragraph 4.7.

4.5.13. Bistar

Bistar played a large role in formulating the GTAG and ISO standards. They used a basic Supertag Switch-off protocol, but with different randomization algorithms.

4.5.14. Trolleyponder

Marsh *et al* [40] have patented a variation on the Supertag protocol in an attempt to bypass the Supertag patents. In their protocol, instead of tags switching off after receiving an acknowledgement from the reader, they switch off automatically after transmitting their IDs, unless the reader indicates that a collision or other error has taken place. As it is quite likely that tags can in fact transmit without the reader detecting it, this protocol is likely to have a very high error rate.

4.5.15. Auto-ID / Alien

The MIT Auto-ID EPC standard [82] specifies two different anti-collision protocols for HF and UHF applications:

- *HF*

The HF anti-collision protocol is a slotted Aloha protocol similar to the ISO 18000-6 Type A and the Philips I-Code.

- *UHF*

The Auto-ID EPC UHF anti-collision protocol is an octal search in which the IDs are queried three bits at a time. Tags respond in one of eight bins depending on the value of the three bits queried.[3]

4.5.16. ISO

The ISO committee (ISO/IEC JTC 1/SC 31/WG 4/SG 3 N311) could not agree on a single protocol. The ISO 18000-6 standard therefore describes two protocols [84]:

- *Type A:*

The Type A protocol is a referred to as a "slotted Aloha" and is very similar to the "framed Aloha" used by Philips in their I-Code products (see paragraph 4.5.8). The collision arbitration mechanism allocates tag transmissions into rounds and slots. A round consists of a number of slots. When the reader initiates the anti-collision or census process each tag randomly selects a slot in which to respond. The number of slots in a round is determined by the interrogator and signalled to the tag. During the subsequent collision arbitration process the interrogator dynamically chooses an optimum number of slots for the next round based on the number of collisions in the round. The number of collisions is a function of the number of tags present. After the initialisation process, the reader opens each slot and checks for tag transmissions. If a single tag transmission is received, the tag is put into a quiet state. The reader next closes the slot and moves on to the next slot, until all slots have been examined, whereupon a new round can be started.

[3] Auto-ID has since proposed a new protocol [84] that seems to be a mixture of ISO 1800-6 Type A and B, but includes some options to separate the reader and tag spectra. There are, however, a number of problems with this protocol, mainly concerning its complexity and security aspects [160].

Unlike other protocols the ID is not used for collision detection, but rather a 6 bit random number and a 4 bit signature. The 6 bit random number may be the last 6 significant bits of the UID, or may be generated on the fly. The signature serves as a transient identification and could also be generated on the fly or could e.g. be related to the Tag's Excitation Level (TEL). The idea here is apparently to support tags with identical IDs.

- *Type B:*

The Type B protocol implements a non-deterministic binary tree search. The protocol can be summarised as follows: After the reader has given a command to initialise the anti-collision arbitration, tags randomly generate a '1' or a '0'. Tags with '0' transmit their IDs, whereas tags with '1' put their ID transmissions on a stack. If only one ID is received, the reader can record it or exchange other data with that tag. This tag does not take any further part in the arbitration process. If one or no ID were received, the reader indicates success to the remaining tags, which then decrements their stack counters. Those with their stack counter at zero can next transmit their IDs when requested to do so. If a collision is detected, the reader indicates the failure to the tags, which then randomly either increment their stack counters or leave them unchanged.

4.6. Supertag

The series of protocols developed at CSIR during the 1990s and now licensed by BTG are collectively known as the Supertag protocols. Strictly speaking, the "Free-running" protocol does not fall under the Supertag patents, but as it forms the basis of the Supertag protocols, they will be grouped here. The Switch-off and Slow-down protocols were already implemented in the H4021 chip as early as 1992. An 'Acknowledge' was transmitted as a single 100% modulated pulse or 'gap' in the RF field, i.e. the reader power beam is momentarily turned off. The Fast protocol was added in the P4022 in 1998. As a single gap was needed for the Mute function, the Switch-off or Slow-

down acknowledge was changed to a double gap. The Fast protocol can be combined with the Free-running, Switch-off or Slow-down protocols to give six different protocols. The P4022 can be programmed for 8 different intervals and 8 different baud rates. Only the 64k baud rate and the 4k and 16k interval setting were considered useful in practice.

4.6.1. Free-running

In the Free-running protocol, tags transmit their IDs intermittently with random intervals between the transmissions. There are no transmissions from the reader. A programmable parameter sets the maximum interval between transmissions and the intervals between transmissions are randomly distributed between zero and the maximum. The protocol tends to saturate easily, so that the same maximum interval cannot be used for a few fast-moving tags and a large number of slow-moving tags (See Figure 35).

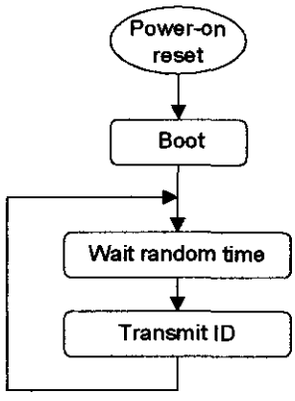

Figure 24: Free-running protocol flow diagram

In the practical implementation of the protocol on the H4021 and P4022 chips an LFSR pseudo-random number generator is used. This generator is seeded at boot time. The Free-running protocol can be adapted to approximate the iP-X protocol by specially selecting seeds for the LFSR pseudo-random number generator. The V22 and V32 versions of the P4022

are programmed with seeds selected from a list of 4k values out of the total possible 64k values. These values were selected so that the first two intervals would be below half the nominal value, with the third interval above half the nominal value. This guarantees that, on average, the first two intervals will be shorter than normal.

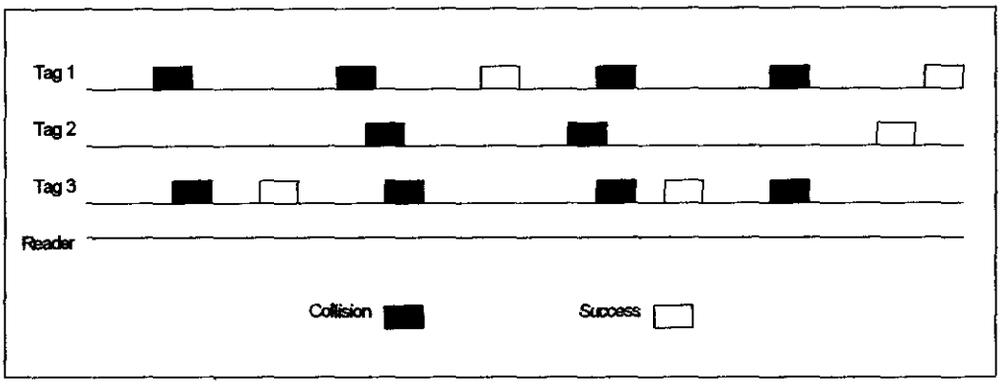

Figure 25: Free-running protocol sequence.

4.6.2. Switch-off and Slow-down

In an attempt to alleviate the saturation problem a technique was invented whereby the reader acknowledges a successful ID reception and the tag switches itself off upon reception of the acknowledgement. In the Slow-down variation, the tag does not switch off but just reduces its transmission rate. Both have the effect of reducing the total number of tag transmissions and thereby the number of collisions.

In the H4021 and P4022 implementations tags stay off until a power-on reset occurs. In the Bistar implementation this switch-off state is maintained by a flag that decays after some (indeterminate) time. The Switch-off protocol is approximately four times faster than the Free-running protocol, but is limited in baud rate due to spectrum regulations.

The main advantage touted for the Switch-off invention is that it allows the detection and counting of tags with identical IDs, as might occur when tags

were programmed with product codes instead of serial numbers. In the proposed EPC numbering scheme the feature becomes moot, since a serial number is included so that identical product-coded items could be distinguished by their serial number.

This acknowledgement is synchronised to the tag transmission, so that ideally only the tag that has just transmitted will react to the acknowledgement. Unfortunately a real possibility exists that two or more tags will transmit close together, to the point where the acknowledgment is synchronised to all of these overlapping transmissions. If one of these tags finds itself close to the reader or in a peak caused by multi-path propagation, while the other(s) find themselves in a weaker area of the field, it is likely that the reader will not detect a collision and will generate an acknowledgement, thereby switching off some tags without ever detecting their presence. This leads to an error rate that cannot easily be avoided and which increases with an increase in tag population (see also Figure 33). The Slow-down version was added in order to reduce the error rate caused by inadvertent switching-off, but this of course requires unique IDs or serial numbers.

It is worth noting that the ISO 18000-6 Type A protocol, which has Supertag features in it, attempts to overcome the problem of inadvertent switch-off by adding a 6-bit random number and a 4-bit signature to the tag transmission. The 6-bit random number could be the last 6 significant bits of the UID, or could be generated on the fly. The 4-bit signature could be generated by a TEL function, giving a level of spatial diversity. Instead of the very simple double-gap Acknowledge of Supertag, the signature is added to the Acknowledge, which mitigates the problem of not detecting weakly transmitting tags to a large extent.

The Switch-off protocol of course also suffers from the other drawbacks as discussed in Par. 4.4.2

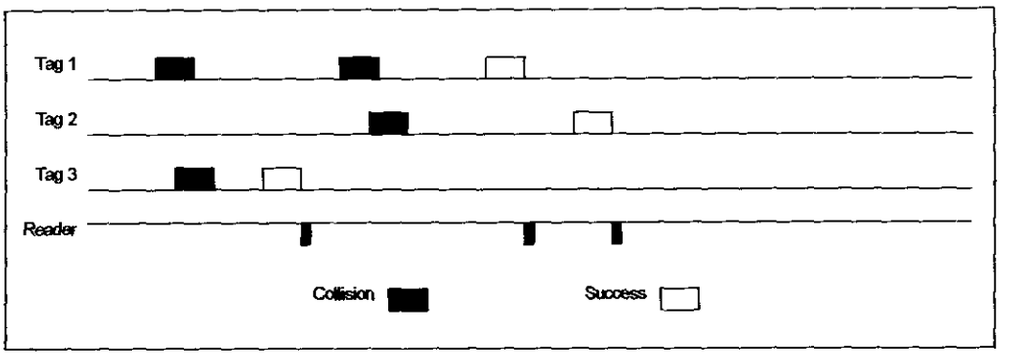

Figure 26: Switch-off Supertag protocol sequence

4.6.3. Fast

In the Fast protocol the reader sends a Mute signal in the form of a single gap as soon as a tag transmission is detected. This causes all the other tags to halt their Tx countdown sequences for 128 clocks before continuing, allowing the first tag to finish its transmission without any collisions. Only in the case when two tags start up close together can there still be a collision.

The Fast protocol achieves an acceleration factor that is dependant on how soon the Mute signal can be sent after the start of a transmission. The reader must first try to make sure that it is in fact getting start bits from a real tag transmission and not just noise. If it reacts too often on noise, it will be muting the tags all the time. Also note that a few start bits are lost, making the filters in the reader more difficult to implement.

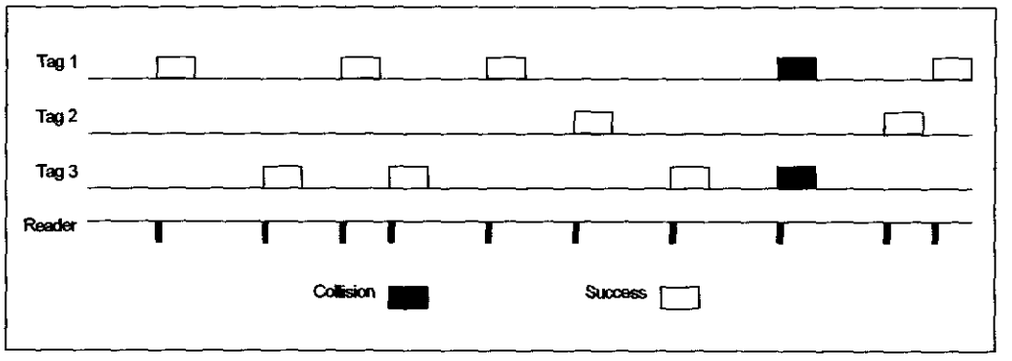

Figure 27: Fast Free-running Supertag protocol sequence

4.6.4. Fast Switch-off or Slowdown

The greatest potential acceleration can be achieved by combining the Fast and Switch-off or Slow-down protocols. Almost all collisions can be avoided and saturation is almost non-existent.

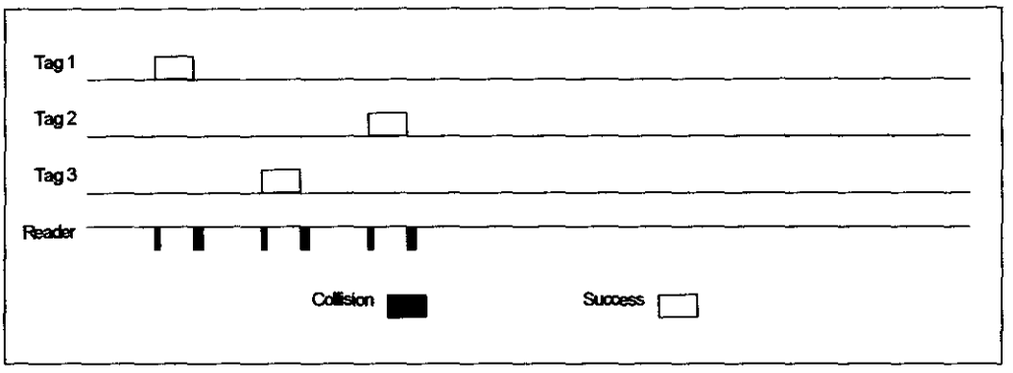

Figure 28: Fast Switch-off Supertag protocol sequence

4.7. iP-X

4.7.1. Read-only

The iP-X read-only protocol is implemented in the iP-X1, iP-X2 and iP-X3 chips [114],[115],[116]. *It is very similar to the Free-running protocol on which the Supertag protocol is based.* Tags transmit their IDs codes intermittently with random intervals between the transmissions. There are no transmissions from the reader. A programmable parameter sets the maximum interval between transmissions and the intervals between transmissions are randomly distributed between zero and that maximum.

The main difference between the iP-X and the Free-running protocols is that the dynamic range of the iP-X protocol is improved by reducing the maximum interval for the first few transmissions. In the iP-X chips, the maximum interval starts off at one-eighth the programmed maximum interval. The maximum interval is then doubled every two transmissions until it reaches the programmed value. This results in faster reading times for small numbers of tags, while having little effect on the reading times for large numbers of tags.

One of four maximum intervals can be selected: 1 kbits, 4 kbits, 16 kbits or 64 kbits. The 4 kbit interval allows for reading tags travelling at very high speeds – up to 360 km/h. The 64 kbit interval setting allows for reading very large numbers of tags. This setting saturates above 800 tags but can still read tags travelling at 5 m/s, making it ideal for Supply Chain Management.

Although the iP-X chips can be programmed with four different interval settings and four different baud rates for a total of sixteen combinations, five protocol variations have been defined (See Table 3 below). The V1 and V2 versions are directly compatible with the V22 and V32 versions of the P4022.

Protocol version	Baud rate	Maximum Interval
V1	64k	4k
V2	64k	16k
V3	256k	4k
V4	256k	16k
V5	256k	64k

Table 3: iP-X standard protocol versions

4.7.2. Read/Write

The Read/Write (R/W) protocol as implemented in the iP-X4 chip [117] uses exactly the same anti-collision algorithm as the Read-only protocol. The Read-only and R/W protocols are therefore compatible and Read-only tags and R/W tags can thus be mixed in one application. When the reader receives a tag ID successfully, it can interrupt the anti-collision sequence in order to communicate on a one-on-one basis with the tag, using the last 48 bits of the tag ID as an identifier.

The Read/Write protocol is slightly modified in the iP-X5 chip [118]. The algorithm will stay the same, but instead of just transmitting an ID, tags will have the ability to transmit an EPC code as two 64 bit packets, using the serial number for anti-collision purposes (Native EPC mode).

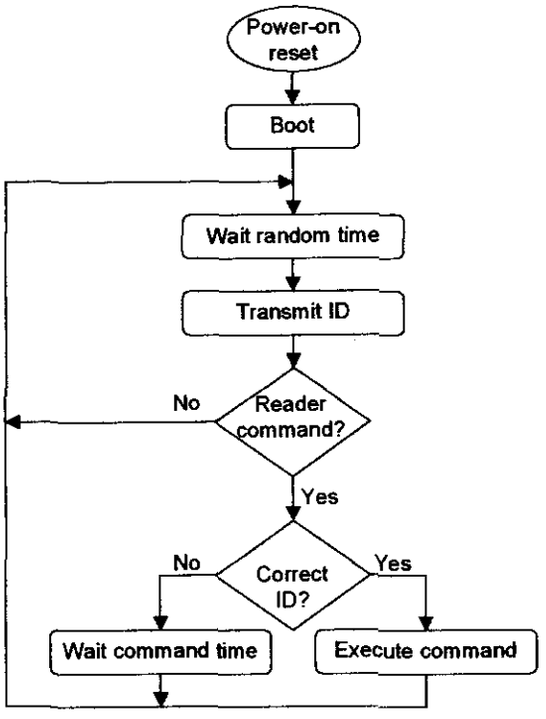

Figure 29: iP-X R/W protocol flow diagram.

4.8. RFID simulator

The RFID simulator was developed by the author to predict the behaviour and performance of a protocol when configured with the parameters of the tag chips that were developed. It is notoriously difficult to develop such a simulator when the practical nature of the tag chips and a rudimentary RF field must be incorporated.

Mathematical analysis of stochastic processes such as the Aloha-based protocols is problematic. Do Manh Anh *et al* [139] analysed the probability of collisions in a simple slotted Aloha system, finding that the probability of two tags colliding is equal to C_2^n / m, where n = number of tags and m = number of slots. However, when the randomness of the on-chip oscillator is added and tags are moving through a complex pattern of peaks and nulls caused by multi-path propagation, mathematical attempts to answer questions such as maximum speeds, reading rates and error rates becomes impractical.

An RFID simulator [121] was developed to analyse and quantify the performance of the Supertag and iP-X protocols, specifically parameters such as reading rates, maximum speeds, error rates and saturation levels. The simulator was also used to develop design parameters for the P4022 and iP-X series chips and to analyse typical RFID applications.

4.8.1. Overview

The simulator allows the user to define an application scenario, i.e. numbers and types of tags, speeds and direction of movement. A rudimentary field strength model simulates the effects of nulls and peaks and consequent protocol resets and restarts.

A single simulation run reports the time taken to read all tags and the associated error rate. Simulations can be repeated multiple times to get statistical results such as average read times, maximum read times and standard deviation. Simulations can also step through parameters such as number of tags, speed or interval.

4.8.2. Application modelling

A specific application is modelled by entering the number and speed of tags that will typically move along a predefined path past a reader. The physical group length (distance between first and last tag in the group) and path width must also be defined. Tags can be randomly or regularly distributed in space. For purely theoretical protocol simulations a static simulation can be executed. If the protocol parameters are known, these can also be entered and the application envelope (numbers and speeds of tags that can be reliably handled) can then be determined using the simulator. If the application envelope is given, the simulator can be used to determine the optimum protocol parameters (mainly maximum interval).

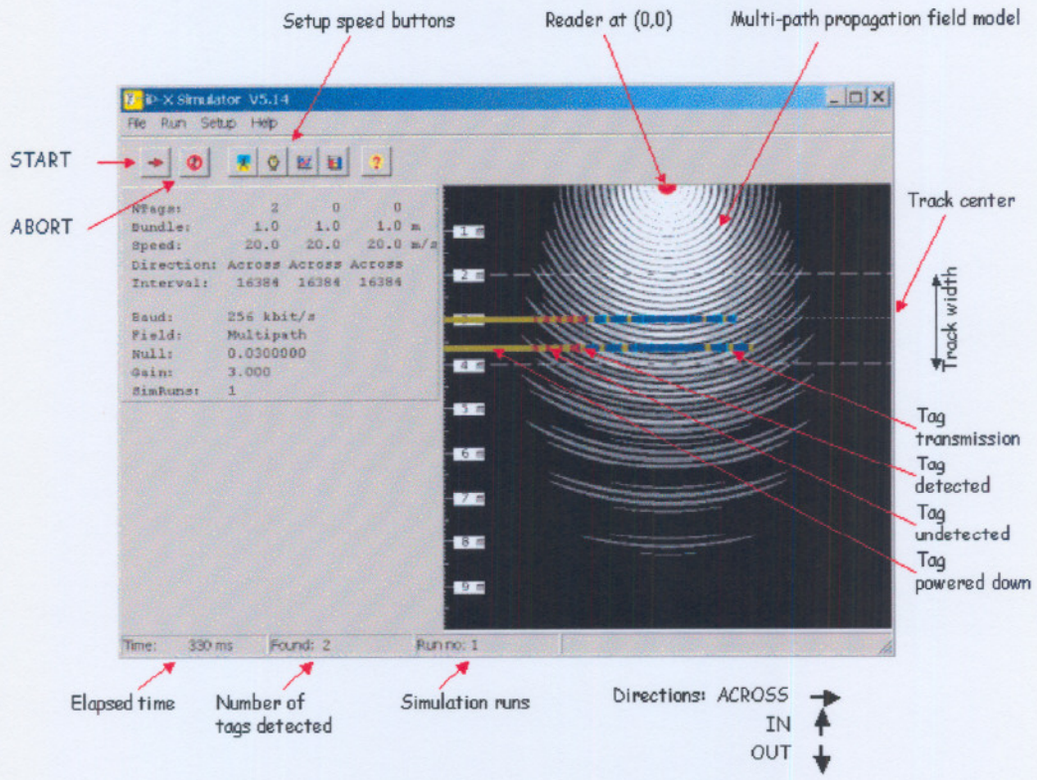

Figure 30: The RFID simulator user interface.

4.8.3. Field modelling

Rudimentary two dimensional field modelling is done to generate realistic peaks and nulls, so that protocol behaviour can be modelled in various "stop-start" scenarios. The simulator also models varying strength backscatter replies, based on the rudimentary field model.

The simulator does not simulate the RF field in all its detail (including obstructions, reflectors etc) or reader and tag RF performance in the field. Thus, the simulator cannot be used to simulate reading range *per se*. Actual reading range will vary with reader power as determined by country-specific spectrum regulations and the very unpredictable RF environment. Reading range will also vary with the type of tag, orientation of the tags and other environmental conditions, making application testing a requirement for success in the field.

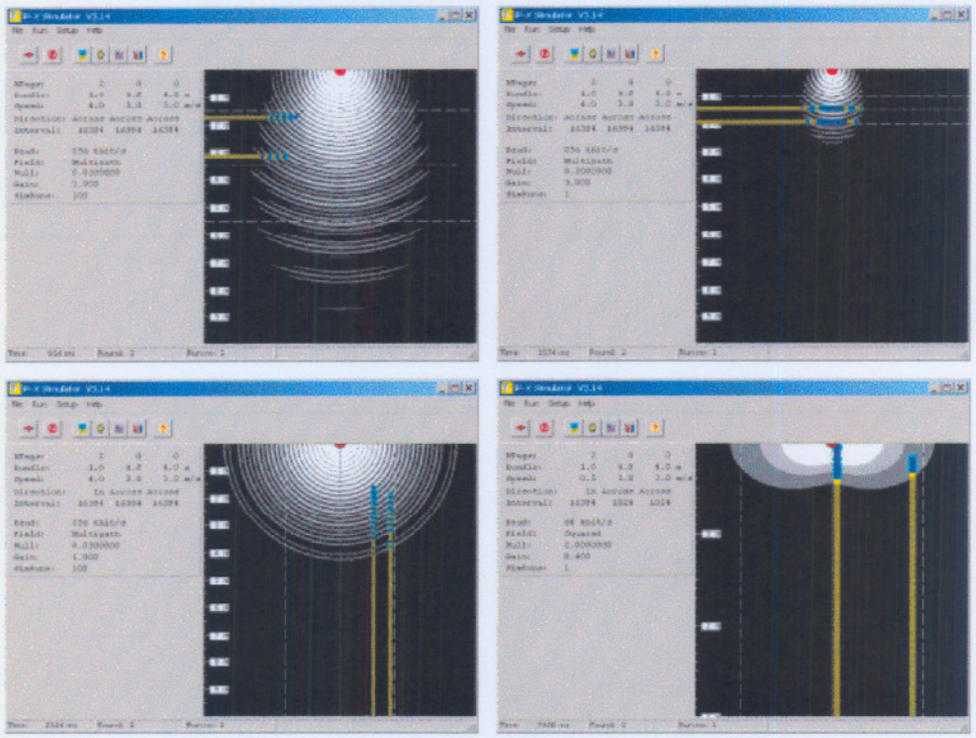

Figure 31: Examples of field patterns (Top left: High gain, high power reader. Top right: High gain, low power reader. Bottom left: Omni-directional reader. Bottom right: Low gain, low frequency reader).

4.8.4. Event driven simulator

The core of the simulator is an event driven "logic" simulator. Tag and reader behaviour is broken down into discrete states. Whenever a state transition takes place, the time to the next state transition is calculated and placed on a stack. The main simulator engine retrieves these event times from the stack, and evaluates the reader's state and all the tags' states at that time. Collision detection is done between tag transmissions and reader transmissions and successful ID receptions are logged.

4.8.5. Simulation results and analysis

The RFID simulation results plotted in Figure 32 to Figure 34 below show typical average reading time distributions for the Free-running protocols and the Supertag Switch-off and Fast Switch-off protocols obtained from the simulator. In all three cases a theoretical "static" simulation was done, i.e. the tags did not move and an RF field with no multi-path propagation (as would be the case in an anechoic chamber) was modelled.

The 'tail' that is a characteristic of these protocols is evident, i.e. the longest time required to read a specific number of tags can be much higher than the average. Although the iP-X chip data sheets quote the average times, a practical application should probably use 3σ values, unless a certain error rate can be tolerated or the transaction can be repeated in case of an error.

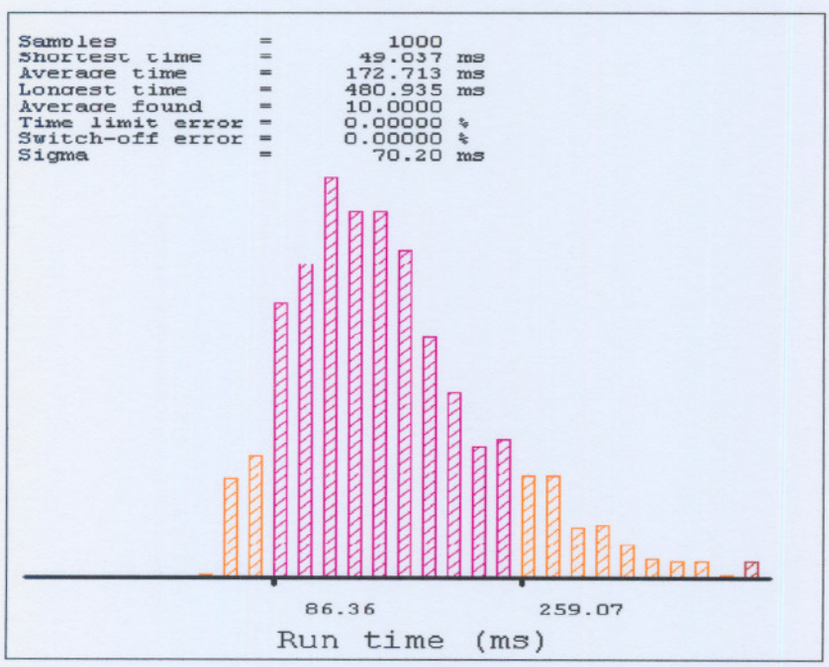

Figure 32: Average reading time distribution for the Free-running protocol (10 tags, 64k baud rate, 64k interval)

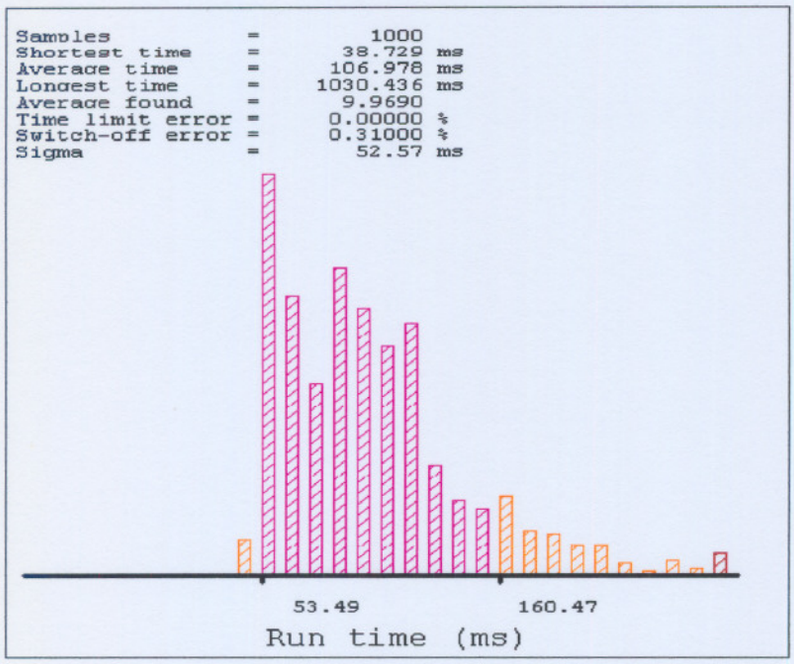

Figure 33: Average reading time distribution for the Switch-off protocol (10 tags, 64k baud rate, 64k interval)

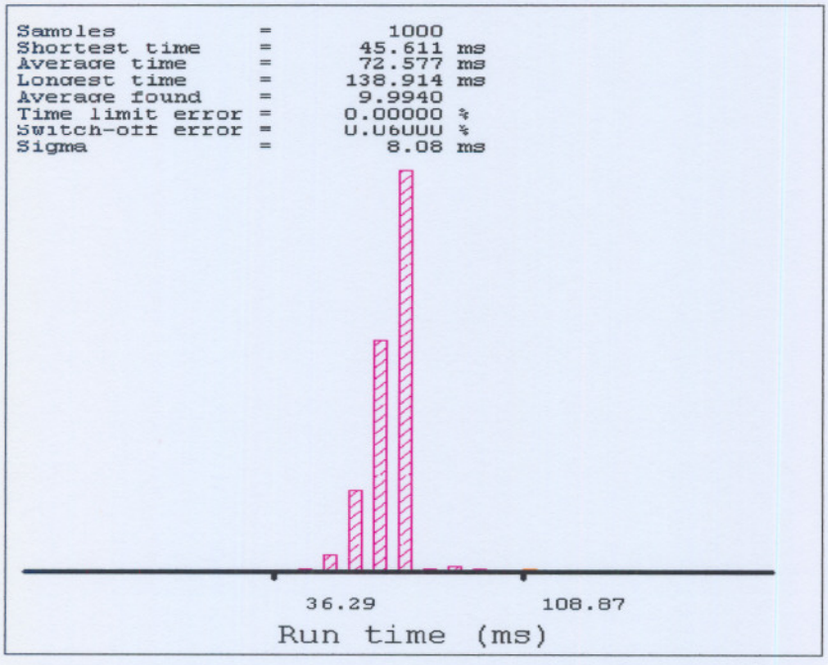

Figure 34: Average reading time distribution for the Fast Switch-off protocol (10 tags, 64k baud rate, 64k interval).

Figure 35 below shows the effect of saturation. All the graphs are for 64k baud rates and 4k intervals. Each point represents the average taken over 100 simulations. The Free-running and iP-X protocols saturates at about 50 tags, while the saturation in the other two protocols is negligible.

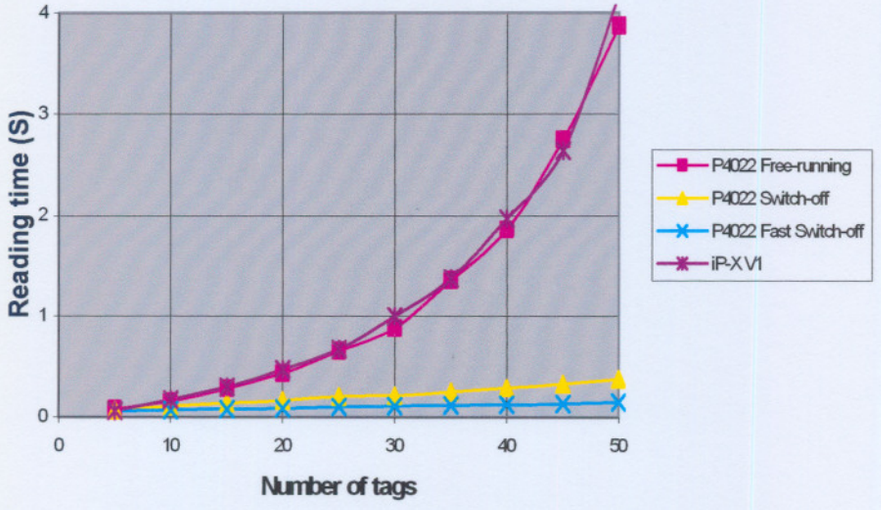

Figure 35: Protocol saturation.

Figure 36 below shows the rising error rates for the Switch-off and Fast Switch-off error rates. At the point where the Free-running and iP-X protocols reach saturation, the error rate for the Switch-off protocol has risen to more than 2%.

Figure 36: Error rates

Figure 37 below shows the average reading times for the five variations of the iP-X protocol. As can be seen, the V4 and V5 protocols can on average read more than 100 tags in one second.

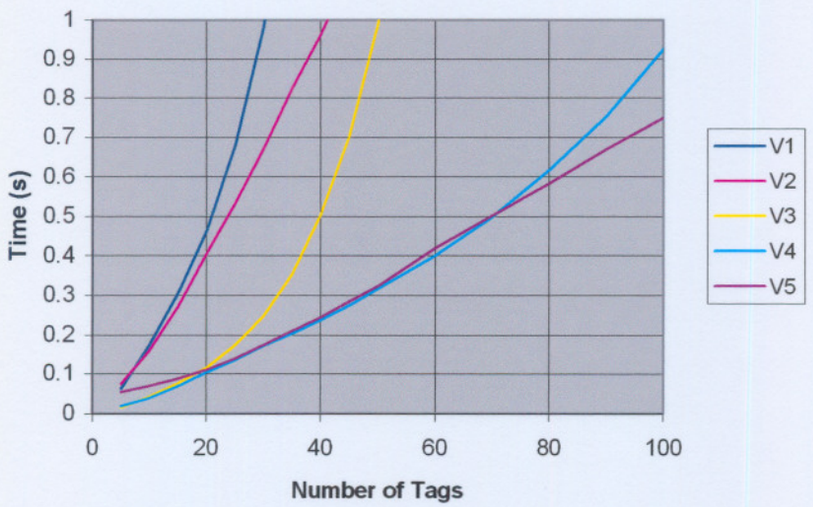

Figure 37: Average reading times for the iP-X protocols.

Figure 38 below shows the maximum simulated reading rates for the iP-X protocols. As can be seen, reading rates in excess of 300 tags per second can be reached with the V3 and V4 protocols for small numbers of tags (less than 5 tags).

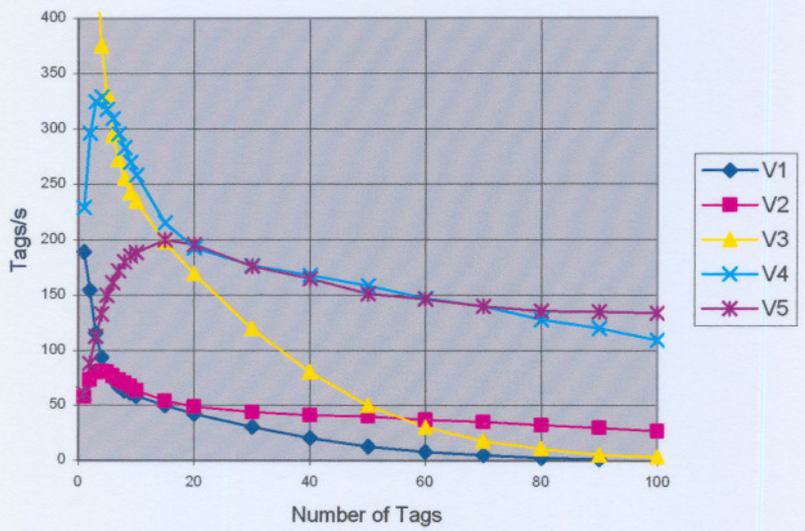

Figure 38: Maximum reading rates for the iP-X protocols.

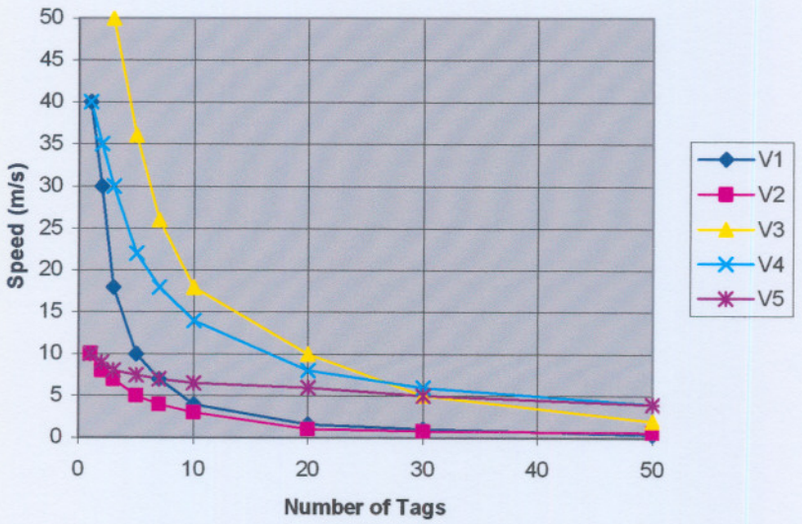

Figure 39: Maximum travelling speeds for the iP-X protocols

4.9. Conclusion

In this chapter we compared the iP-X air protocol to various other protocols in use today, as well as to other Aloha type protocols. Using a software simulator to extract the predicted performance of the protocol, it was shown that the protocol can in fact read large numbers of fast moving tags and meets the basic requirements for supply chain management today. Reading rates in excess of 300 tags/s can be reached, while objects moving at velocities in excess of 250 km/h can be identified successfully. The accuracy of the simulator was verified by actual measurements, while the overall performance was successfully demonstrated (See Chapter 5).

5. CHIP DESIGN

5.1. Summary

The final requirement for a successful RFID *air protocol is that it must be* ***practically realisable*** *in a silicon chip with as small an area as possible, in order to realise the lowest cost tags possible. As will be shown in this chapter, the iP-X protocol is eminently suitable to be integrated on silicon and results in very small chips. The functionality of these chips that implement the iP-X protocol has been successfully demonstrated in a large number of technology demonstrators and pilot installations. Thus, verification of the success of the tag chips is achieved through measurement of tag performance vs. simulator performance and final validation of user requirements is achieved through user feedback in the form of published reports and announcement of commercial support for, specifically, this iP-X protocol and tags.*

Several chips were designed by the author over the past 14 years. The first chip tested basic UHF RFID principles, followed by the H4021, which for the first time implemented anti-collision protocols, to the iP-X series chips, which implement the iP-X anti-collision protocol (See Table 4). The iP-X chips are now going into their first major pilots worldwide [126] and promise to sell in volumes of several hundred million chips per year in the near future.

Year	Chip	Application	Main features
1989	/*047	Passive UHF RFID	Bipolar 64 bit PROM
1992	H4021	Passive UHF RFID	Free-running, Slowdown and Switch-off protocols Field programmed ID (EEPROM) External UHF rectifier
1998	P4022	Passive UHF and 125 kHz RFID	Fast, Free-running, Slowdown and Switch-off protocols Factory programmed ID (Laser fuse ROM) Read-only External UHF rectifier, internal 125 kHz rectifier
2002	EM4122 (iP-X1)	Passive UHF RFID	iP-X protocol Factory programmed ID (Laser fuse ROM) Read-only External UHF rectifier
2002	EM4222 (iP-X2)	Passive UHF RFID	iP-X protocol Factory programmed ID (Laser fuse ROM) Read-only Internal UHF rectifier
2002	EM4322 (iP-X3)	Passive DF RFID	iP-X protocol Factory programmed ID (Laser fuse ROM) Read-only Internal 125 kHz rectifier
2002	EM4422 (iP-X4)	Passive UHF RFID	iP-X protocol Factory programmed ID (Laser fuse ROM) Read/Write (1 kbit EEPROM) Internal UHF rectifier
2003	EM4232 (iP-X6)	Semi-active UHF RFID	iP-X protocol Factory programmed ID (Laser fuse ROM) Read-only Battery powered
2003	EM4432 (iP-X7)	Semi-active UHF RFID	iP-X protocol Factory programmed ID (Laser fuse ROM) Read/Write (1 kbit EEPROM) Battery powered

Table 4: Summary of chips designed[4]

It is beyond the scope of this thesis to go into any great detail of the chip designs since these designs are simply too voluminous to document in this thesis. In the following section only iP-X RFID specific design aspects will be discussed. This is followed by a short discussion on each of the RFID chips that were designed and implemented.

[4] The iP-X5, a R/W version of the iP-X3 dual frequency RFID chip has since also been designed and is currently being tested and characterised.

5.2. Design aspects

5.2.1. Rectifier and Modulator

Two alternative voltage doubling rectifier / modulator structures were considered, "After diode modulation" and "Before diode modulation". In "After diode modulation" the antenna is decoupled from the modulating transistor by the rectifier diodes. In "Before diode modulation" the antenna is directly driven by the rectifier diodes.

The "After diode modulation" structure is shown in Figure 40 below. In this structure Node A is a low capacitance node and the parasitic capacitances of transistors Q1 and Q2 are of little concern, as these capacitances are decoupled from the antenna by the Schottky diodes. This is an advantage in a process where little is known about the RF characteristics of the transistors. Mainly because of these unknowns associated with the RF performance of the transistors, we have used the "After diode modulation" technique throughout

A so-called "charge preservation transistor" Q2 is required to prevent VDD from being loaded when Q1 is modulating the antenna. Q2 is normally on, but must be switched off before Q1 is switched on and switched on again after Q1 has been switched off.

The design of the charge preservation circuit is critical: At power-up all the transistors are off. In order to "bootstrap" the circuit, it is important that the circuit operates correctly in the sub-threshold region, i.e. transistor Q2 must be conducting more than Q1 in the sub-threshold region. There is also a parasitic substrate PNP transistor in parallel with Q2 and it is important that Q2 turns on before the parasitic PNP. Once Q2 is on, the PNP is held off.

There are two drawbacks:

- Backscatter efficiency is low, as the antenna is modulated through diode D1 [149].

- Because of the critical timing requirements in the switching of Q1 and Q2, it is difficult to implement slope control in order to reduce the level of the high frequency harmonics caused by sharp rising and falling edges.

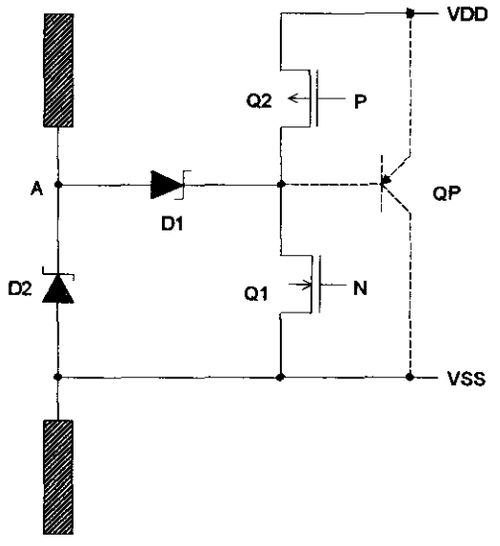

Figure 40: After diode modulation

The so-called "Before diode modulation" structure is shown in Figure 41 below. Here transistor Q1 modulates the antenna directly and no charge preservation transistor is required, provided that the Schottky leakage is low so that VDD is not discharged during modulation. Backscatter efficiency can be higher, provided Q1 is a high frequency transistor with low parasitic drain-source capacitance [149].

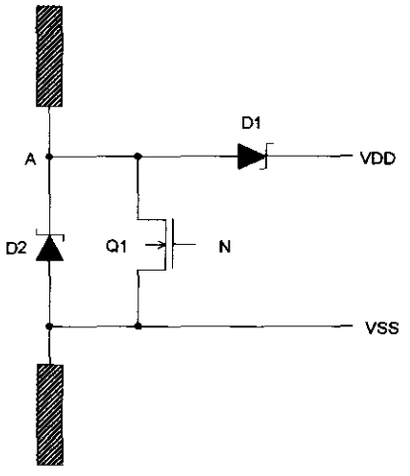

Figure 41: Before diode modulation

An advantage of "Before diode modulation" is that it allows the rectifier structure to be expanded into a charge pump rectifier as shown in Figure 42. This structure has the potential to increase VDD and therefore reading range.

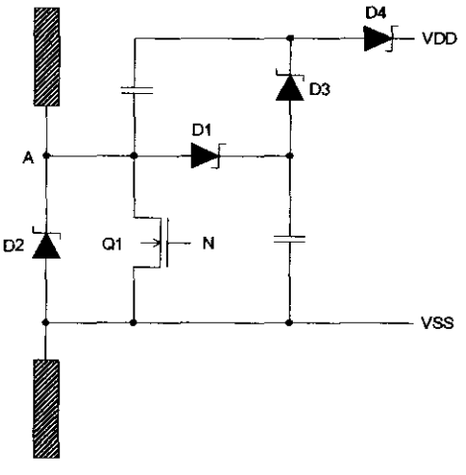

Figure 42: Charge pump front-end

5.2.2. Power-on reset hysteresis

After Power-on reset and during modulation, the chip current increases with a resulting drop in the VDD voltage. In order to prevent the chip from resetting immediately as a result of the voltage drop, the Power-on reset circuit is designed to have approximately 200 mV hysteresis (See Figure 43). This prevents the chip from going into oscillation, possibly only transmitting a part of an ID at short intervals and jamming other tags in the vicinity.

This hysteresis has a side-effect: Tags seem to have a longer reading range when moving away from a reader, compared to moving towards a reader. In real life, of course, tags will always move past a reader, initially moving towards the reader. The shorter reading range is therefore the relevant figure.

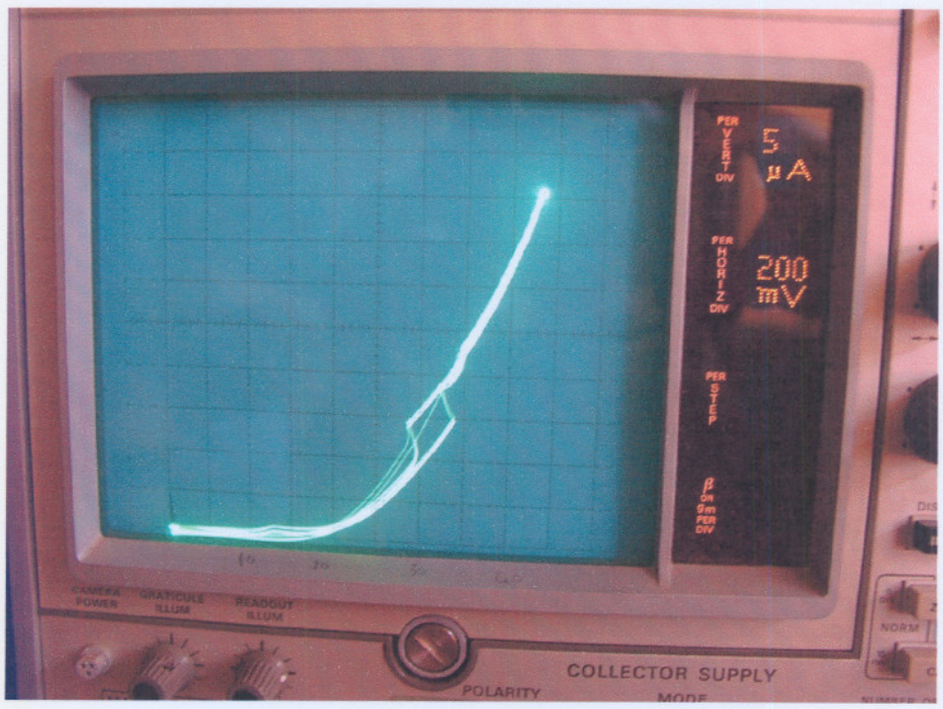

Figure 43: Power-on reset hysteresis

5.2.3. Encoding technique

The chip does not receive any energy from the reader when either the chip or the reader is modulating. During this time the chip has to operate from

charge stored in an on-chip storage capacitor. In order to minimize the size of this capacitor, it is important to minimize the actual modulation time, both of the reader and of the chip.

The encoding technique used is shown in Figure 46 below. The technique is really a pulse position modulation, with a pulse during the first half of a bit period indicating a '1' and a pulse during the second half of a bit period indicating a '0' (See Figure 44 below). It is obtained from Manchester encoding (also shown for reference) by gating (ANDing) the clock and the Mancester code. It requires a higher bandwidth than the Manchester encoding, but has the main advantage that the modulation period is four times shorter than the maximum for a Manchester code. This implies a four times smaller on-chip storage capacitor. Exactly the same encoding is used from tag to reader and from reader to the tag.

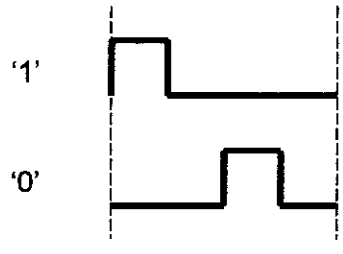

Figure 44: Pulse position encoding.

The modulation technique can also be considered to be a transition encoding where '1' to '1' and '0' to '0' transitions are encoding as a pulse interval of 1 bit, a '1' to '0' transition is encoded as a pulse interval of 1.5 bit and a '0' to '1' transition is encoded as a 0.5 bit pulse interval (See Figure 45 below).

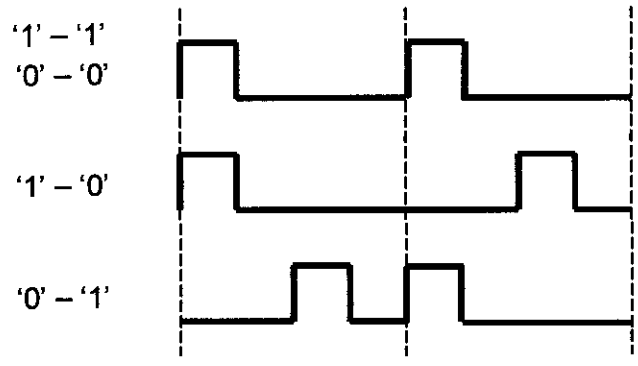

Figure 45: Transition encoding.

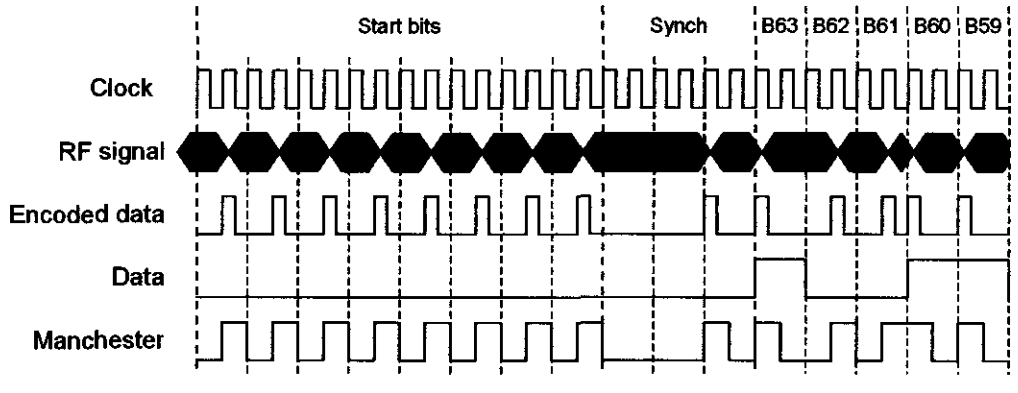

Figure 46: Encoding technique

5.2.4. Protocol engine

A simplified block diagram of the Free-running protocol engine is shown in Figure 47 below. In order to generate a random delay a pseudo-random number generator is implemented by means of a Linear Feedback Shift Register (LFSR). The LFSR is initialized at power-up with a factory programmed seed value. A bit counter is clocked until it compares to the value in the LFSR, at which point one ID is transmitted, the bit counter is

reset and the LFSR is clocked to generate the next pseudo-random number. The simplicity of this engine results in a very small chip size.

By specially selecting a subset of seeds from the 2^{16}-1 possible seeds, the initial behaviour of the engine can be controlled to achieve a deceleration effect similar to that achieved with the iP-X protocol.

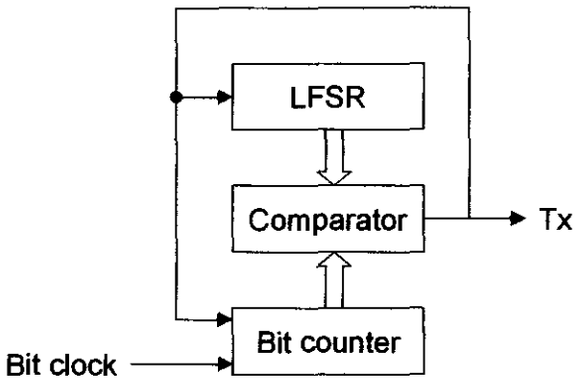

Figure 47: Free-running protocol engine

The iP-X protocol is based on the Free-running protocol. A simplified block diagram of the iP-X protocol engine is shown in Figure 48 below. Like the Free-running protocol an LFSR is used to generate a pseudo-random number, which is compared to a bit counter to generate an ID transmission. The main difference is that the width of the comparison can be automatically adjusted. The comparison width starts off narrow and is then automatically increased after every two transmissions. This has the effect that the interval between ID transmissions increases after every two transmissions. As explained in Par. 4.7, this results in a wider dynamic range, with the initially fast transmissions catering for small numbers of fast-moving tags, while the slower transmissions later cater for large numbers of slow-moving tags.

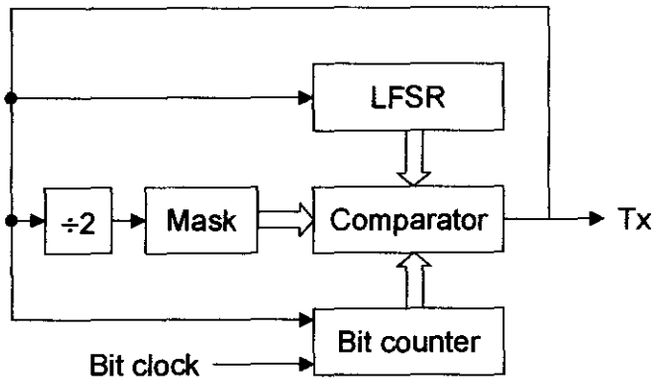

Figure 48: iP-X protocol engine

5.3. Tag implementation and verification

Verification of the design implementation is done by means of functional capability tests and visual presentation of the tag chips that were designed. Since functional capability is a "GO / NO-GO" test, it may seem a rather unimpressive result by means of a simple confirmation of success. Nevertheless, this is the final result and no more is required to confirm the functional capability of these devices. A visual inspection of the tag chips serves to show the actual implementation of the iP-X protocol on silicon. The following paragraphs will provide the verification of the success of the technical development of tag chips (presented as a series of individual developments over the past 14 years).

*5.3.1. /*0147*

The /*047 was a 64-bit bipolar PROM that used the principle of Zener-zapping to program bits. It was accompanied by a low-voltage digital gate array. These chips were designed to test the principles of UHF RFID, as discrete implementations invariably consumed too much current, were physically too large and interfered with the radiation pattern of the dipole antennas.

5.3.2. H4021

The H4021 was specified in September 1992 and designed in November 1992. EM Microelectronic supplied the oscillator and Power-on Reset cells,

while the logic and system schematic design were done locally and recaptured on the EM CAD system (Compass) at EM in Marin, Switzerland. The chip was manufactured in a 3 µm low power CMOS process with EEPROM capability. The process was chosen for its ability to work down to 1.2 V. Prototype samples were received in February 1993 and proved to be fully functional. Most of the design aspects and architecture, still in use today in the P4022 and iP-X series, were developed for the H4021.

Unlike its followers, the H4021 was fully programmable, i.e. an ID was not factory programmed, but could instead be field-programmed into its EEPROM. This EEPROM consumed more than half the chip area.

The H4021 was the first chip in the series to implement anti-collision protocols. Three protocols were implemented, namely the Free-running and Slow-down protocols (See Par. 4.6.1 and Par. 4.6.2), which form the basis of the iP-X protocol, as well as the Switch-off protocol (Par. 4.6.2).

The chip did not contain an on-board UHF rectifier. The antenna was modulated by switching a MOS transistor across the external rectifier ("After diode modulation"). One of the first problems to be solved was how to prevent the modulator from discharging the storage capacitor during modulation. The "Charge preservation circuit" (See Par. 5.2.1) was invented to solve this problem. This circuit was also used in the P4022 and is still used in the iP-X series.

At first a single UHF Schottky diode was used as a half-wave rectifier and reading ranges of 4 m were achieved with reader transmit powers of more than 40 W eirp (up to 150 W eirp was sometimes used). When a voltage-doubling (peak-to-peak) rectifier was implemented using X-band Schottky diodes, reading ranges of more than 40 meters were demonstrated. Reader transmit power could now be reduced dramatically while still achieving usable reading ranges.

5.3.3. P4022

The P4022 was designed under contract to Mikomtek and BTG in May 1998. It was implemented in a 1 µm low power CMOS process, once again at EM Microelectronic. It built on the design of the H4021, but the main aim was to reduce the chip size down to a level where the cost of the tags would make them attractive for large-scale exploitation. No means existed yet for implementing a UHF rectifier on-chip, so the chip still required an external Schottky rectifier. The current consumption / baud rate ratio also necessitated an external storage capacitor. Unfortunately a decision to also make it usable for 125 kHz RFID applications resulted in a chip that was not as small as was originally intended. The final chip size was 2.5 mm^2 (see Figure 49).

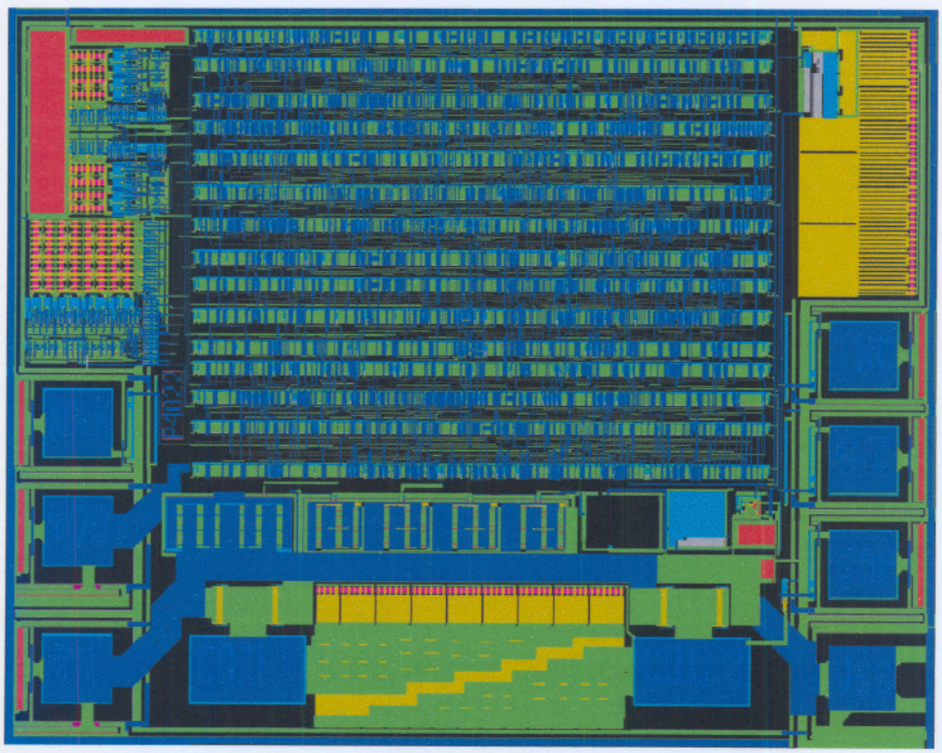

Figure 49: P4022 layout

The block diagram of the P4022 is shown in Figure 50 below. Apart from the 125 kHz full-wave rectifying bridge and tuning capacitor (which are of no concern as far as this thesis is concerned) the main differences from the H4021 are as follows:

- A shunt regulator / limiter was added to protect the external Schottky diodes against over-voltage.
- Instead of using an EEPROM, the ID was factory-programmed into a laser fuse ROM. This reduced the size of the chip and the current consumption dramatically, compared to the H4021.
- The Fast protocol (Par. 4.6.3) was added to the protocols implemented in the H4021, so that the P4022 was capable of executing six different protocols (Free-running, Slow-down, Switch-off, Fast Free-running, Fast Slow-down, Fast Switch-off). In order to achieve this, the pulse used to acknowledge an ID reception in the Switch-off and Slow-down protocols was changed to be a double pulse, so that a single pulse could be used for the Fast Mute function.

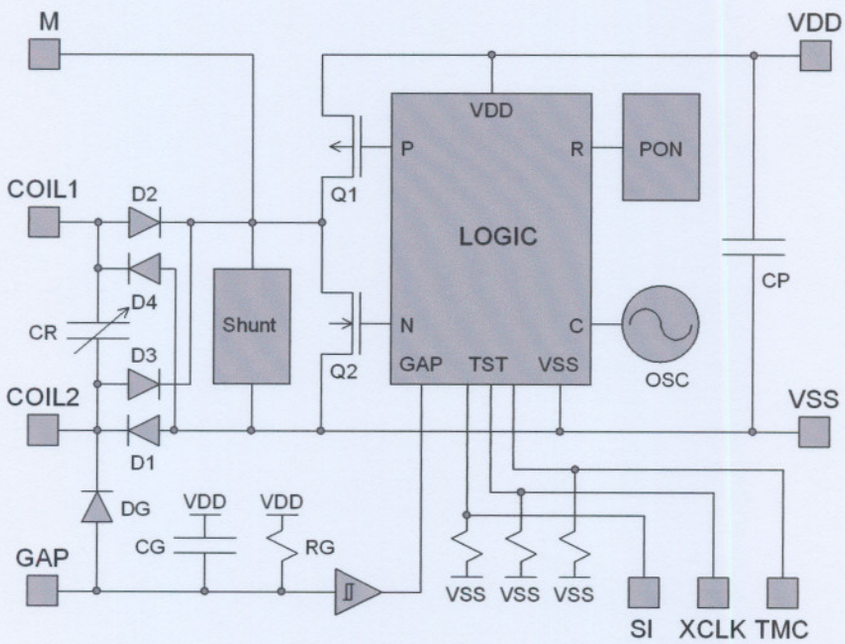

Figure 50: P4022 block diagram

In special versions of the P4022 the seeding algorithm of the pseudo-random number generator was changed to achieve an effect similar to the deceleration of the iP-X protocol. Instead of merely assigning a random number as a seed value, seeds were selected from a table of values that would result in initially decelerating number sequences. Although the P4022 never achieved large-scale production, it was used until 2003 for demonstrations and small pilots. Reading ranges of about 3 m at 500 mW erp, 8 m at 4 W eirp and more than 30 m at 30 W eirp were achieved. Reading of up to 80 items simultaneously and reading of single tags at up to 180 km/h were demonstrated (See Paragraph 5.4).

5.3.4. iP-X

The iP-X *series of chips* was the result of a joint venture between iPico Identification and EM. The main aim was to reduce chip size to an absolute minimum, keeping only the absolute minimum functionality, while at the same time removing all licensing restrictions. This mainly meant discarding the problematic Supertag family of protocols in favour of the iP-X protocol. The SEED ROM was also discarded and instead the least significant 16 bits of the ID (the CRC) were used as a seed for the pseudo-random number generator. To improve throughput and move the data spectrum further away from the carrier, the maximum baud rate was increased to 256 kbit/s.

In order to reduce chip size to an absolute minimum, it was decided to use EM's new 0.5 µm low voltage CMOS process. This process also offered a possibility of both N and P substrate Schottky diodes. The number of pads was reduced and pad size was reduced from the standard 120 µm x 120 µm down to 80 µm x 80 µm, and scribe margins were reduced to the absolute minimum. *The overall result was chips that were nearly an order of magnitude smaller than their predecessors (See Figure 51 below).*

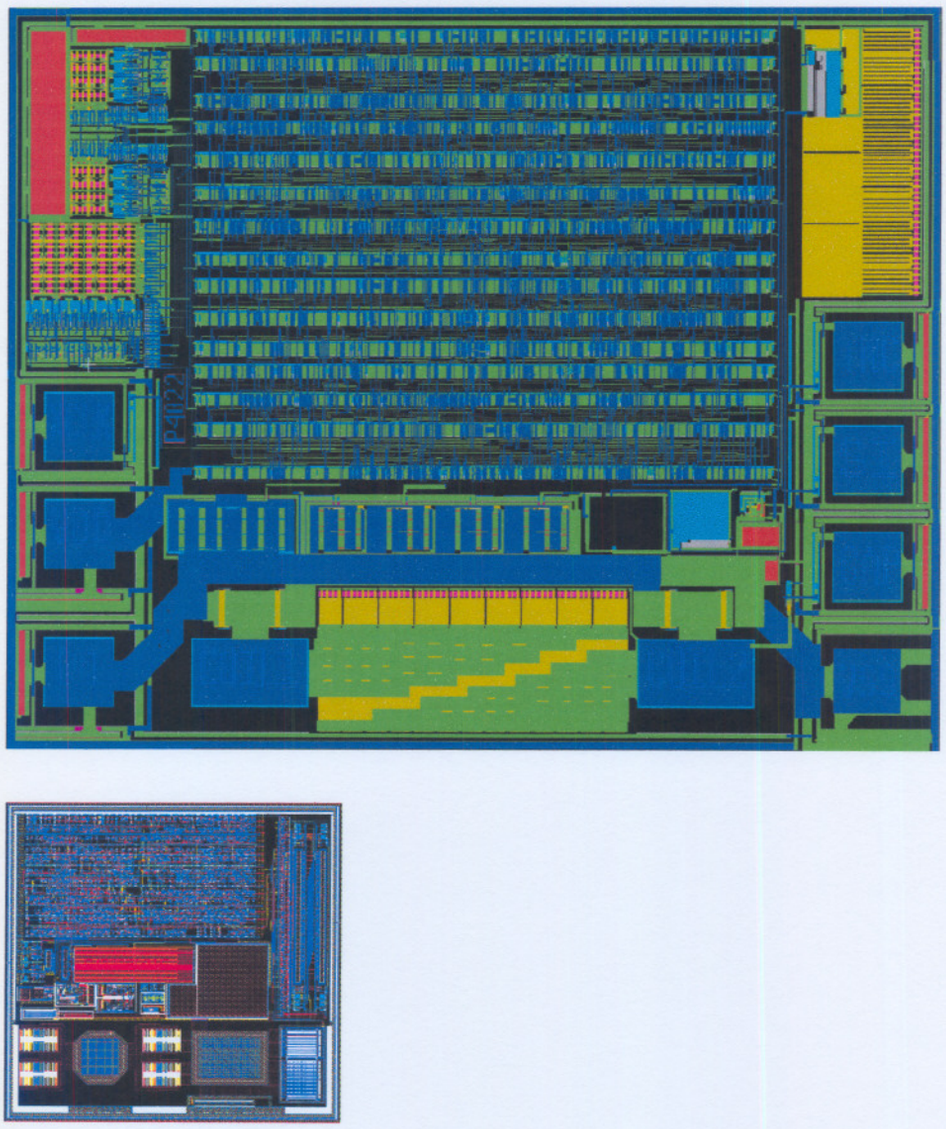

Figure 51: Size comparison between iP-X2 and P4022

P4022: 57 x 69 mil = 1.448 mm x 1.753 mm = 2.54 mm^2

IP-X2: 0.675 mm x 0.654 mm = 0.44 mm^2

Area ratio = 5.8

The size of a tag chip (in terms of its area) is the main commercial cost driver of a chip. It is shown above that a reduction in chip size by a factor of 5.8

was achieved, which enabled the tag chip to become a major competitor in the market in terms of cost [126],[128],[129],[130],[131].

5.3.5. iP-X1 (EM4122)

The iP-X1 chip was intended as a low risk upgrade to the P4022. As little was known about how the integrated Schottky diodes would perform, the iP-X1 was designed to use an external rectifier. When the iP-X2 chip performed beyond expectations, the iP-X1 development was terminated after it had been successfully tested and characterized [145].

The first prototype design of the iP-X1 was done in May 2002. The first design was fully functional but has been superseded by the iP-X2.

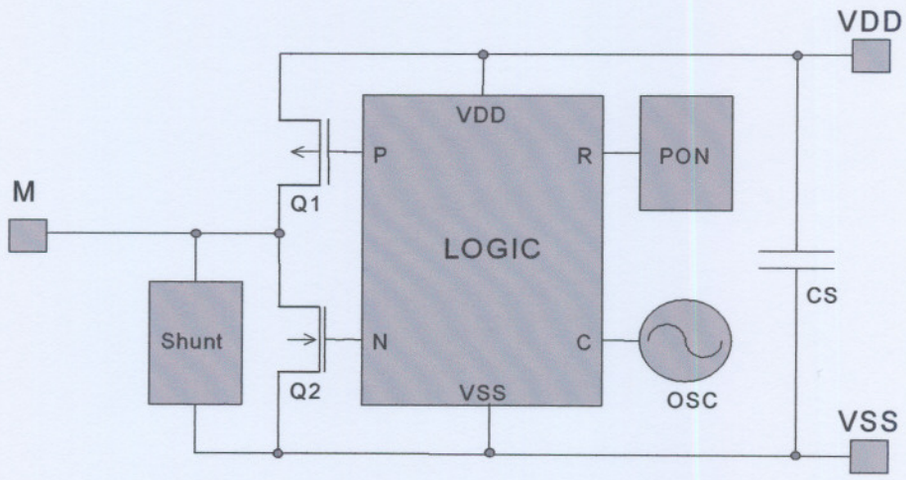

Figure 52: iP-X1 block diagram

5.3.6. iP-X2 (EM4222)

The iP-X2 chip is the same as the iP-X1, with the addition of an integrated Schottky diode rectifier. *This chip made a single component tag possible for the first time - an additional important design achievement that improved the manufacturability and reduced manufacturing costs even more.* Reading range was found to be 80-90% of

the P4022 reading range. *The extremely small size (< 0.5 mm²) and no external components make very low-cost tags possible - thus achieving the design goal of low cost*

The first prototype design of the iP-X2 was done in May 2002. This design turned out to be fully functional and production started in March 2003. *Several hundred thousand chips have already been produced, and it is expected that sales will run into several hundred million per year in the near future* [126],[128],[129],[130], [131]. *This is conclusive evidence to validate the chip as a solution in the market.*

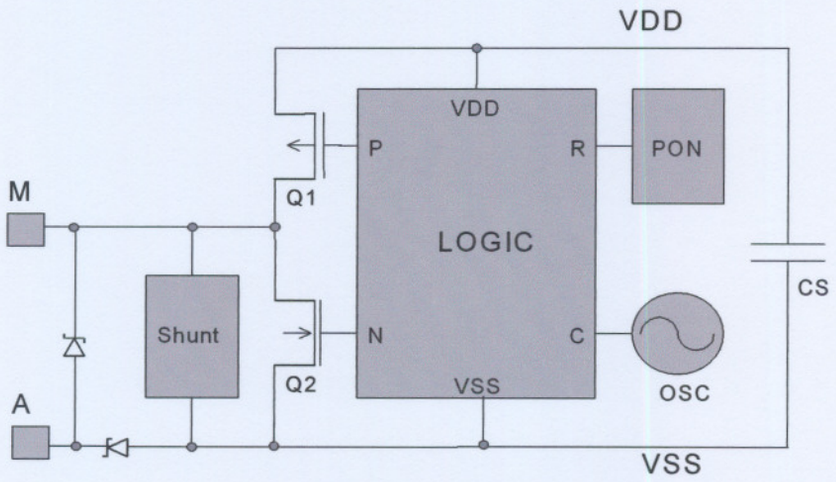

Figure 53: iP-X2 block diagram

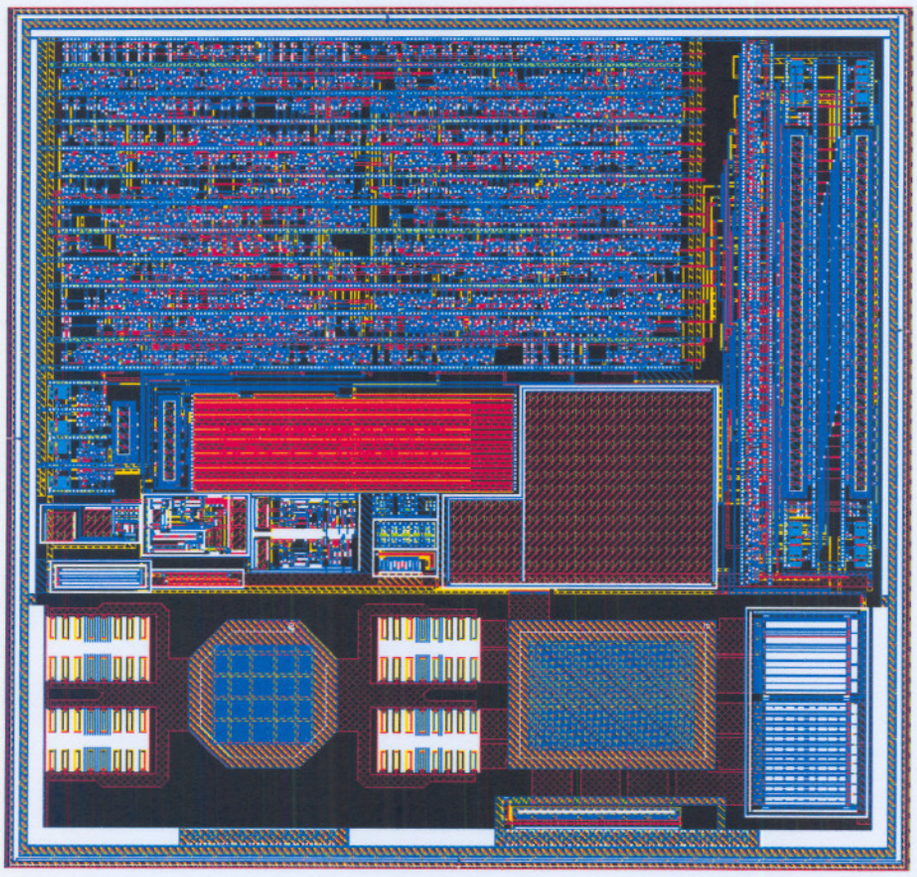

Figure 54: iP-X2 layout

5.3.7. iP-X3 (EM4322)

The iP-X3 chip is intended for dual frequency applications and as such it falls outside the scope of this thesis. However, the chip forms an integral part of the overall development and a short discussion on the success of the chip is presented for interest sake. The chip is powered at 125/134 kHz and transmits back at 6.8 MHz or 13.56 MHz, and is mainly used for people and animal tracking. It demonstrates the applicability of the iP-X protocols for frequencies other than UHF.

The iP-X3 was designed in May 2002 and production started in April 2003. It has been used in several pilots, notably in South African mines where its ability to be read through conducting substances is required [154].

5.3.8. iP-X4 (EM4422)

The iP-X4 is a Read/Write version of the iP-X2. It executes the R/W variant of the iP-X protocol and contains 1 kbit of EEPROM memory organized as 16 pages of 64 bits each. The first 15 pages are user-accessible, but the last page is used to store system information.

Commands and data from the reader are AM modulated on the carrier and received by means of a Schottky diode detector and data extractor. This is followed by a simple digital filter. Although the transmission from the reader is accurately timed, it can appear to the chip as if it is drifting in frequency, because the chip's own oscillator drifts. A tracking decoder is therefore required for reliable data extraction.

The anti-collision protocol and all commands, with the exception of the WRITE command, can be executed at the minimum supply voltage (about 1.1 V), and therefore at maximum range. The EEPROM requires a minimum of 2.1 V for a WRITE cycle, which means that WRITE commands can only be executed at closer range.

Prototypes of the iP-X4 were manufactured during 2003. These prototypes have been tested and characterized [146] and the design will be put into production early in 2004.

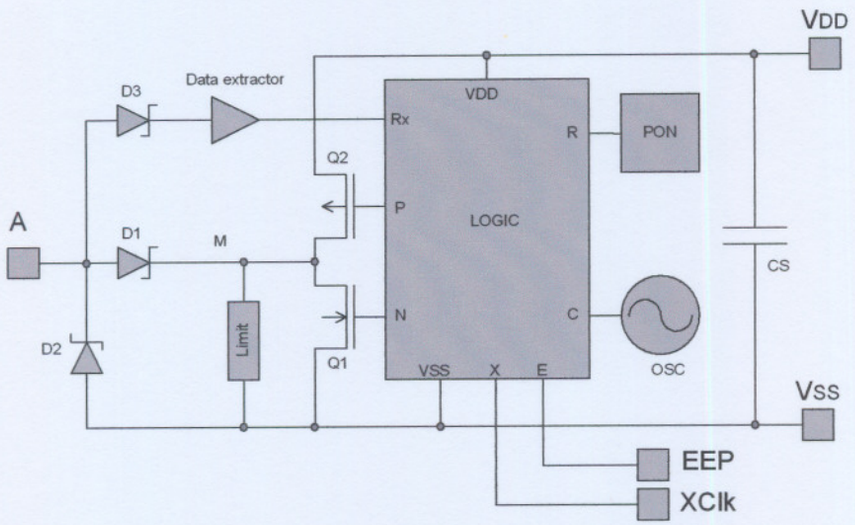

Figure 55: iP-X4 block diagram

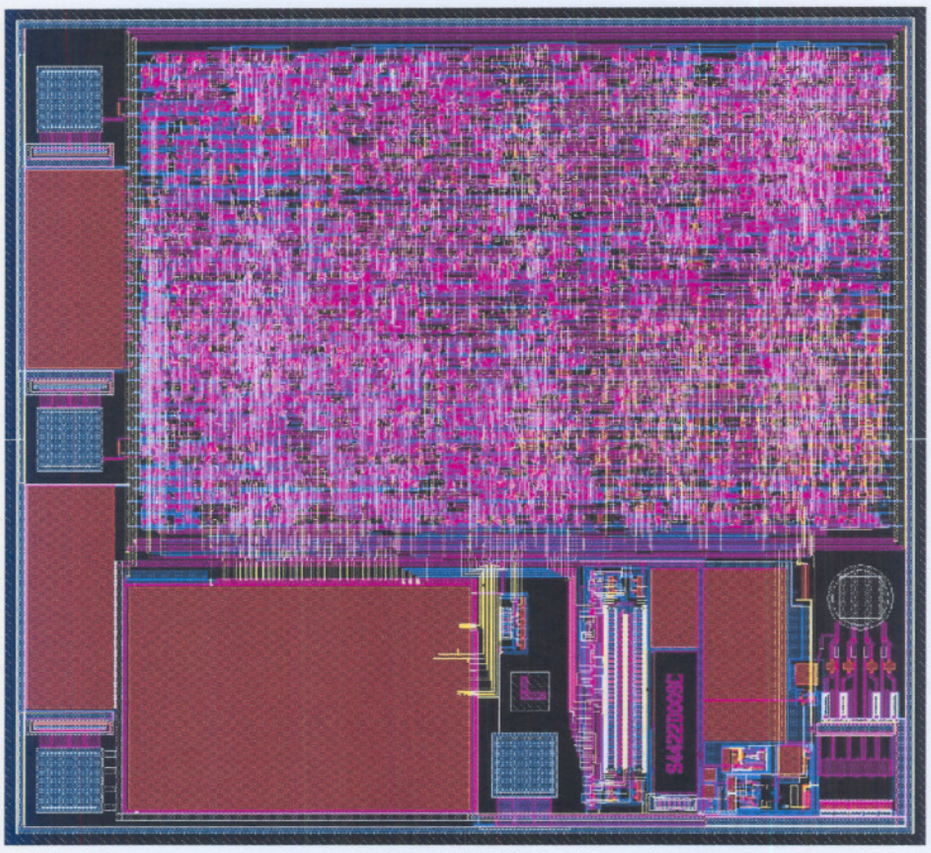

Figure 56: iP-X4 layout

5.3.9. iP-X6 (EM4232)

The iP-X6 chip was designed in May 2003 [147]. It is a semi-active or battery-assisted version of the iP-X2. Instead of extracting power from the reader beam by means of a rectifier, the chip is powered by a battery. The main advantage is extended reading range, because power range is normally the limiting factor in passive UHF tags. To achieve the longer range, the tag reader must be 20 dB more sensitive.

In order to achieve a lifetime of at least three years with a 30 mAh battery over the full temperature range, the current consumption must be below 200 nA. The only way of achieving this is by adding a low current standby mode to the chip. A field sensor turns the chip on when it enters the reader beam. This sensor must be sensitive enough to turn the chip on at the longer range, but not be so sensitive that stray electromagnetic fields (readers, cell phones and cell phone base stations, etc.) cause the battery to be discharged unintentionally.

Transmission of IDs back to the reader is still by means of backscatter. Unlike an active tag, a semi-active tag must be in a reader beam in order to transmit an ID. An important difference between a passive tag and a semi-active tag lies in the fact that, because no power transfer is required from the antenna to the tag, the modulator can be optimized to achieve maximum backscatter efficiency (ΔRCS).

The iP-X6 layout is shown in Figure 58. Chip size is up from the iP-X2, mainly because an additional pad is required for the battery connection.

Prototypes of the iP-X6 were manufactured during 2003. These prototypes were extensively tested and characterised [149] and a production design was finalised during December 2003 [148].

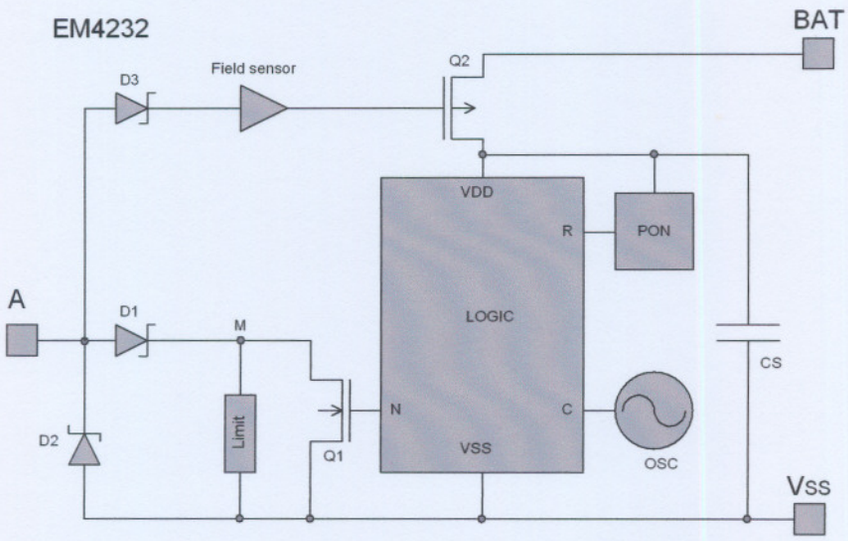

Figure 57: iP-X6 block diagram

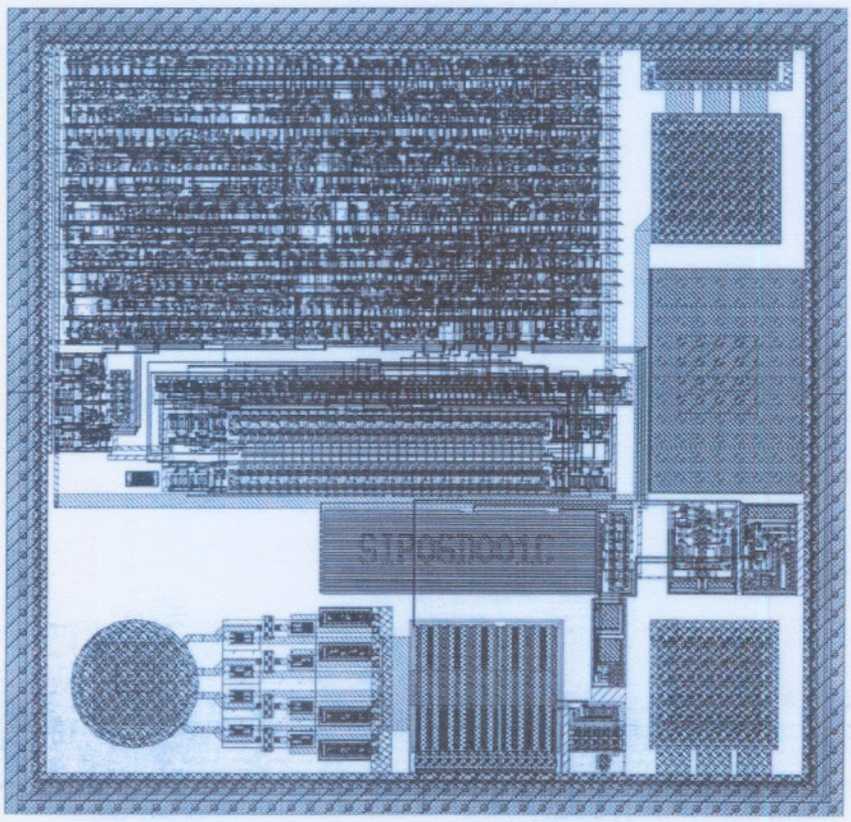

Figure 58: iP-X6 layout

5.3.10. iP-X7 (EM4432)

The iP-X7 chip was designed in May 2003 [147]. It is a R/W version of the iP-X6 and is in all aspects compatible with the iP-X4. Prototypes of the iP-X7 were manufactured during 2003. These prototypes were extensively tested and characterized [150]. A production design was completed in December 2003 [148] and production of this chip has now been launched.

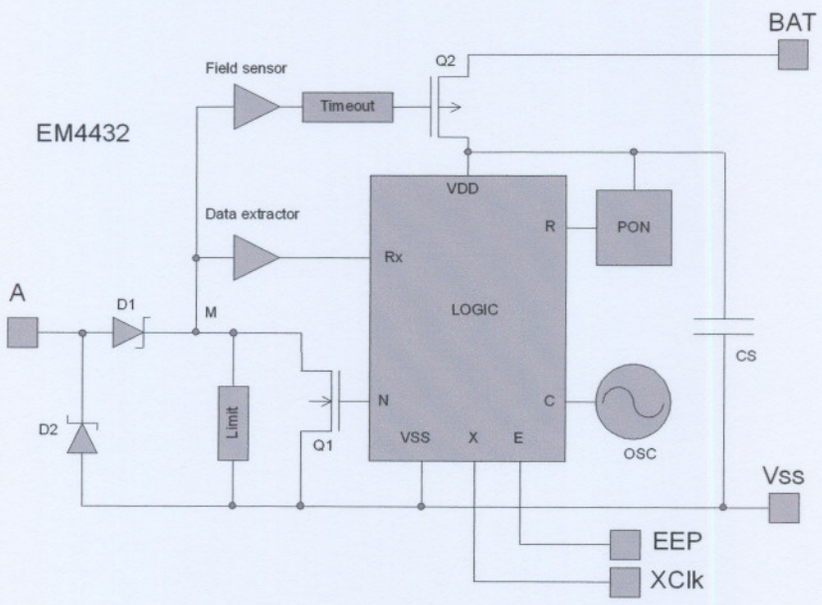

Figure 59: iP-X7 block diagram

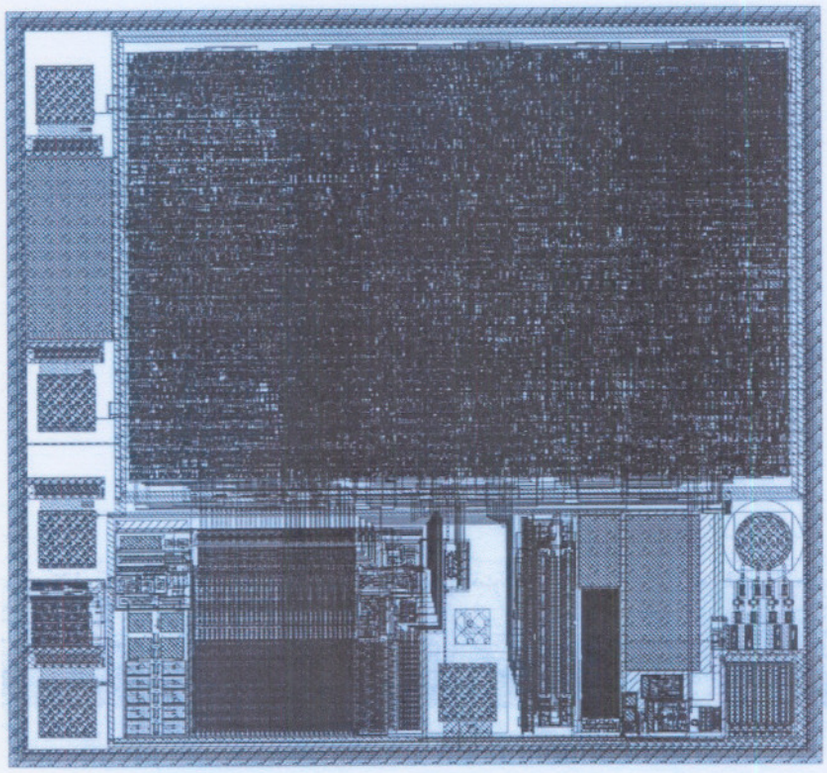

Figure 60: iP-X7 layout

5.4. Protocol verification

In order to demonstrate the performance capability of the tag chips as well as the accuracy of the simulator, it is necessary to graphically depict the tag measured results against the predicted results from the simulator. This serves to provide final confirmation of the (i) performance capability of the tags when used in a system, and (ii) the usefulness and success of the simulator as part of the system's development support.

The graph below (Figure 61) shows the measured performance for the Free-running protocol as implemented in the P4022 and the iP-X protocol as implemented in the EM4222.

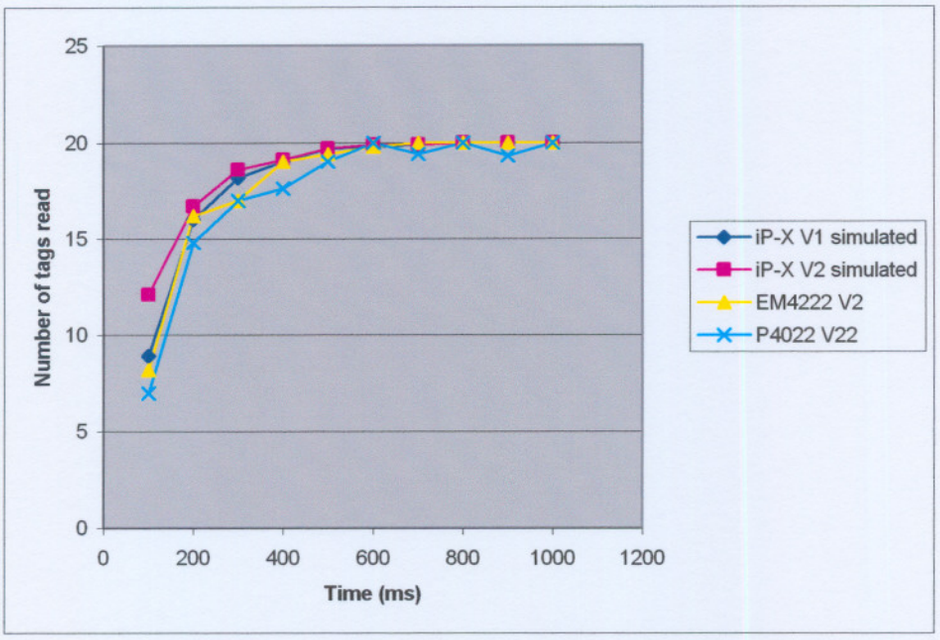

Figure 61: Measured protocol performance

As is seen from the graph, the actual measurements correlate extremely well with the predictions of the simulator. The minor differences between measured an simulated results at very short times can be ascribed to the start-up models used in the simulator which may be adjusted ("tweaked") to describe the tags more accurately.

The high degree of correlation between tag and simulator performance is the final verification of tag and simulator functional capability and the tag's "in-system" performance capability.

5.5. Application testing

In order to demonstrate the usefulness of the iP-X protocol and tags, it is interesting to see the actual implementation of the tags in field applications. This is not a formal validation process, but serves to demonstrate the versatility of the tag in applications. A number of implementations are discussed in the paragraphs that follow.

The iP-X series chips, as well as the P4022, have been assembled into various tags, ranging from labels and credit card formats to industrial, vehicle, gas cylinder hand wheel tags and shroud tags (Figure 63 to Figure 65).

Tag antennas are usually half-wave dipoles or folded dipoles. Although more exotic antennas have been proposed [158], such as triple wire folded dipoles and series matched dipoles, the problem is that the propagation speed of electromagnetic waves is slowed down by the dielectric material in which the antenna is embedded. Dipole antennas can easily be trimmed for maximum reading range by just adjusting the length of the dipole, while the more complex antennas need to be redesigned for different dielectric material substrates.

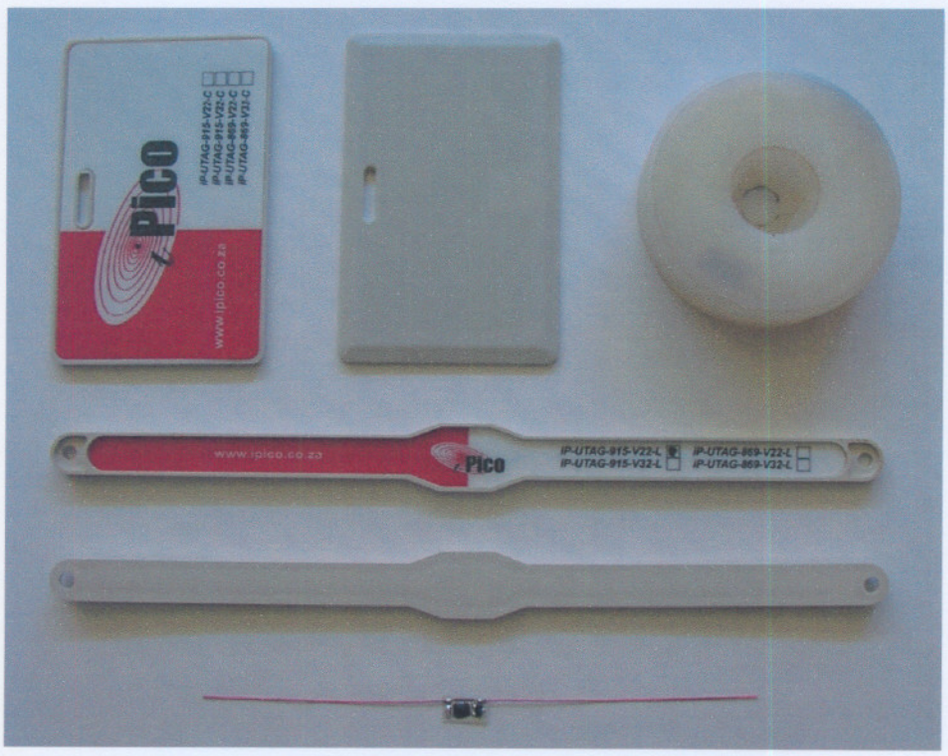

Figure 62: Tag formats: Card, cylinder hand wheel, linear, raw.

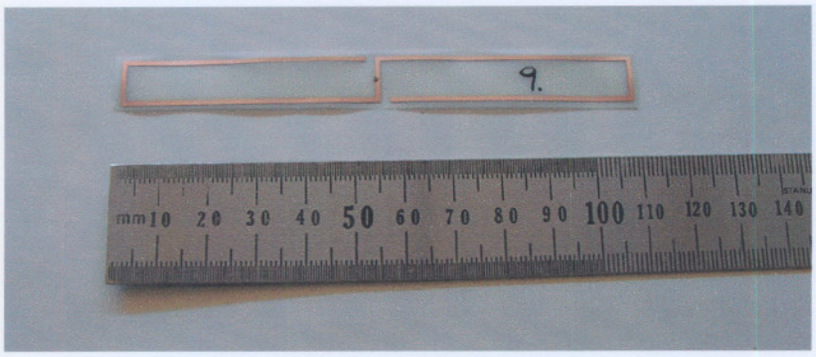

Figure 63: iP-X2 label tag manufactured by Idealtag in France.

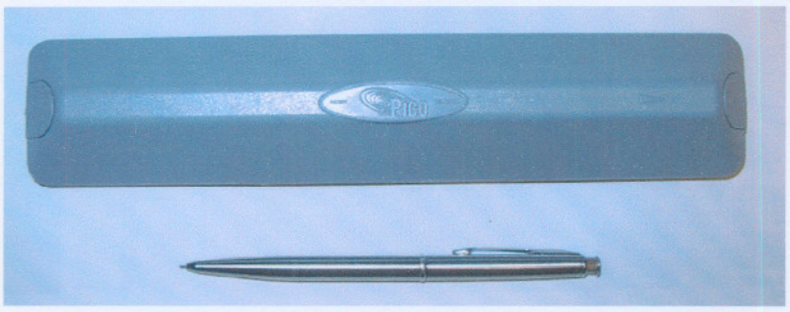

Figure 64: Industrial vehicle tag

Figure 65: Gas cylinder shroud tag

5.5.1. Supply chain testing

The main application area for UHF passive tags is supply chain management. This mainly involves the tagging and tracking of pallets, crates, and gas cylinders. Extensive SCM application testing has taken place [151], [153]:

- Testing with pallets has demonstrated the ability to read 40 pallets simultaneously while they are moved past a single reader through a doorway (Figure 66). The pallets were double tagged to make them readable from all four sides.

Figure 66: Reading pallets on forklift

- Tags were embedded into specially molded cavities in plastic crates (Figure 67, Figure 68). Eighty empty crates on a pallet could be read simultaneously while moving past a single reader.

- A gas cylinder hand wheel tag was designed. The hand wheel was mounted on 90 cylinders. Tests were done to determine the feasibility

of overhead reading of trucks loaded with cylinders (Figure 69 and Figure 70). Two offset antenna pairs were used to avoid interference patterns. A reading rate of 89% was achieved with P4022 based tags. A 100% reading rate should be achievable with iP-X2 based tags, because the iP-X chips can operate at four times the baud rate compared to the P4022, and four times as many tags can be read simultaneously in the same time period..

Figure 67: Tag embedded in plastic crate

Figure 68: Plastic crate with embedded tag

Figure 69: Gas cylinders with tagged hand wheels

Figure 70: Gas cylinder test

5.5.2. Sports application testing

Although not a very lucrative market, sports applications provide a tough testing ground for tags:

- In professional cycle racing the riders often finish in a bundle at high speed and no technology can currently satisfy all the requirements. In our testing with a professional cycle race (Figure 71) and two mountain bike events we achieved a 90% reading rate. The failures could be ascribed to human error: missing tags, upside down or incorrectly oriented tags, etc., as well as inadequate path coverage. Although the results were promising, the tags were not very user-friendly due to the fact that the tags require standoff from a human body.

- Human error could be largely excluded in tests where the tags were mounted on a vehicle and a 100% result was achieved in 4x4 off-road racing tests (Figure 72).

Figure 71: Cycle race test

Figure 72: Off-road 4x4 race testing

5.6. Conclusion

In this chapter, it was shown how the iP-X protocol was practically realised in silicon to achieve the following objectives, namely (i) functional capability, (ii) tag and simulator performance verification, and (iii) tag cost-effectiveness by means of size reduction.

It was shown that the protocol could be implemented in a very small area chip. The EM4222 for example, is less than 0.5 mm^2 and can be manufactured for less than USD 0.05 in very large volumes. It is expected that this price will come down to less than USD 0.02 within the next few years, finally resulting in labels than cost less than the target of USD 0.05.

The simulator was shown to be accurate, and the measured results from field tests (although brief in terms of presentation) correlate extremely well with the predictions from simulations. This is final verification of the tag's

performance capability and the simulator's usefulness in terms of development support.

A number of high density and high speed tests verified the protocol performance in application - this, combined with the success reports from the field validate the tag's success as a competitive, cost-effective product.

Chapter 6

6. DISCUSSION AND CONCLUSION

In the first chapter of this thesis, system requirements and four derived design requirements for a successful UHF RFID air protocol were listed. Results presented in chapters 3, 4 and 5 then demonstrate how the iP-X protocol and hardware meet these four requirements. The resources that were developed to address each of the design requirements were shown to be functionally capable and were verified to meet the additional requirements.

This chapter summarizes the work done in the thesis. Firstly, the developed resources are discussed and verification of their effectiveness is given. Secondly, it is shown how the design requirements were effectively addressed. A discussion on each of the requirements is given, together with a discussion on how the technology (in terms of process or material) addressed the requirements.

6.1. Resources

The following resources were developed in this work, namely (i) an anti-collision protocol, (ii) a simulator, and (iii) a series of cost-effective integrated circuit tag chips.

1. The functional capability of the tag chips and protocol is verified in detail test reports [126],[128],[129],[131],[132],[145],[146],[147],[148], [149],[150],[151],[152],[153],[154],[155]. This, together with the results in Figure 61 serves to prove the fact that the chips are functionally capable.

2. The spectral analysis (refer to Figure 11 and Figure 12) and reader proximity analysis in section 3.8.5 provide verification that readers for the iP-X protocol may be placed in close proximity.

3. Proof of the protocol simulator's accuracy was given in Figure 61. The usefulness of the simulator is further elaborated upon in the simulation results from Figure 32 to and including Figure 39.

4. An inspection test in Figure 51 shows the reduction in cost of the new iP-X tag meets the required goal of a cost of less than 0.05 USD by means of design.

6.1.1. Validation

Validation was achieved by means of application test examples (see section 5.5) and user feedback in the form of marketing and sales figures as well as published commitment towards the iP-X based systems [126],[128],[129], [131],[132],[145],[146],[147],[148],[149],[150],[151],[152],[153],[154],[155] .

6.2. Design requirements

The following design requirements were addressed as set out in the paragraphs that follow. Discussions on each of the requirements and the approach to address that requirement are given to show that the design requirements have been met.

6.2.1. Robustness

The first design requirement was for robustness, hence reduced interference between reader and tags, allowing for simultaneous operation of readers in close proximity. At the same time the protocol had to be robust in the face of complex RF fields. All this had to be achieved while conforming to spectrum regulations.

The iP-X protocol and hardware meet the RF requirements mainly by design. The protocol does not require any wake-up commands or anti-collision steering by the reader, which results in a reader spectrum that is narrow band and separated from the tag backscatter spectrum.

Figure 11 and Figure 12 show measured spectra for the iP-X reader and tag backscatter, confirming that the reader is narrowband and that the tag data spectrum is sufficiently separated to allow filtering of the reader carrier, Doppler components and inter-modulation components. Figure 13 to Figure 15 show reader spectra for three other RFID protocols in use today. These figures show that the reader spectra overlap the tag spectra in these cases, with the result that the reader is likely to interfere with the backscatter. *Mathematical analysis* is used to show that it is unlikely that it will be practical to deploy readers executing the existing protocols in large numbers in close proximity.

The iP-X protocol's robust performance in complex RF fields is the result of the repetitive transmission of ID's at random intervals and the high baud rates used. The high baud rate ensures that ID's can be successfully transmitted in very short windows, while there is inherent redundancy in the repetition of ID transmissions.

6.2.2. Compliance

The second design requirement was regulatory compliance worldwide. This requirement is, like the first requirement, met by design. The narrow band nature of the reader transmission in itself makes conformance to spectrum regulations possible worldwide. An iP-X reader is never active when there are no tags present and also not during the anti-collision phase. In the Read-only case no data is ever transmitted by the reader. In the Read/Write case commands and data are only transmitted in order to access the on-chip EEPROM. This communication occurs rarely and then at a low baud rate.

6.2.3. Anti-collision performance

The third design requirement was for good anti-collision performance. The algorithmic performance of the protocol is proven largely by means of software simulation, but actual measurements as shown in Par. 5.4 confirm the validity of the simulation results. The results indicate that the protocol is both suitable for the reading of large numbers of slow moving tags as might

be found in supply chain applications, and also for the reading of small numbers of fast moving tags, as might be found in Electronic Vehicle Identification (EVI) and sports time keeping applications. As is shown in Chapter 5, the suitability of the protocol and hardware was proven in various application tests, demonstrations and pilot installations.

6.2.4. Chip size

The fourth design requirement was that the protocol must be realizable in a very small and low cost chip. The simplicity of the iP-X protocol guarantees that a minimal sized chip would be possible. As shown in Chapter 5, this requirement was met in the design of the EM4222 chip, which at less than 0.5 mm^2 is the smallest chip of its kind in the world today.

6.3. Conclusion

We have shown that the iP-X protocol is a viable alternative to the UHF RFID anti-collision protocols in use today as well as those proposed as standards. Its main attribute is that it generates little or no reader interference, allowing for large-scale deployment of readers in close proximity. The TTF nature of the protocol leads to low complexity installations with high-speed and high-throughput capabilities. The simplicity of the protocol leads to extremely small chips, resulting in low cost tags. A series of chips has been designed and extensively tested. The iP-X2 and iP-X3 are currently in production and are being used in their first major pilots.

There is currently growing acceptance of the iP-X chips and protocols worldwide. In Europe there is no real competition, as it is the only technology that can give acceptable performance in the very limited European regulatory environment. The use of the EM4222 chip in the publicised Marks & Spencer pilot [126] in the UK demonstrates the acceptance of the iP-X product by a leading Swiss foundry, a French smart label manufacturer, a UK label printer, a UK systems integrator and a major UK retailer. The success

of the pilot itself testifies to the suitability and functionality of the iP-X protocol.

The fact that the iP-X protocols can be used at any frequency, e.g. 125 kHz, 13.56MHz and 2.45 GHz, will also help it to find acceptance in the Far East and in other RFID frequency domains. Even in the United States there is a growing realisation that the reader collision problem is a severe hurdle for their technology offerings.

The current proposed ISO 18000-6 standard seems flawed, in that it does not address the reader interference problem. In the USA there is more support for the Auto-ID initiative than for the ISO standardisation effort. However, it seems likely that the iP-X protocols could establish themselves as de facto standards.

There is some scope for the improvement of the iP-X chips in the future. Specifically a technology such as SOI (Silicon on Insulator) offers much promise with its lower threshold voltages and resultant increase in reading range. Together with voltage multiplier techniques, we hope to increase the reading range of the EM4222 during the next year. Smaller geometry technologies will shrink the die size to the point where the 5c tag will become a reality.

Although the current iP-X4 design is completely Auto-ID EPC compatible, the fact that EEPROM access can only take place at about 2 V, limits its EEPROM reading range and thereby its use as a true EPC device. One of the first projects early in 2004 will be to replace the EEPROM in the iP-X4 with a lower voltage EEPROM in order to create a true EPC device[5].

[5] This has since been done. Qualification of this new device was completed in October 2004.

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