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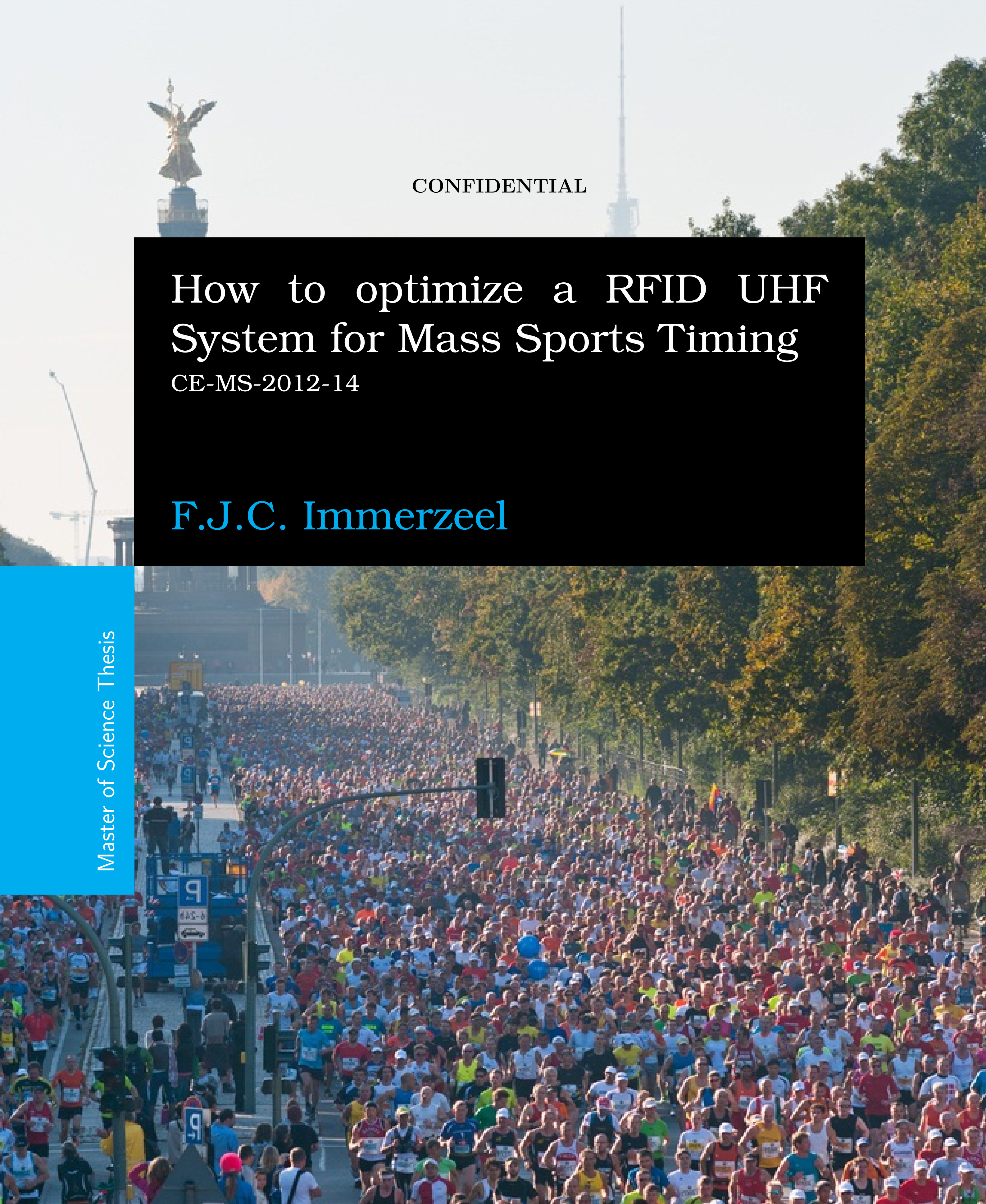
How to optimize a RFID UHF System for Mass Sports Timing

CE-MS-2012-14

F.J.C. Immerzeel

Master of Science Thesis



Delft University of Technology

Embedded Systems

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For the degree of Master of Science in Embedded Systems at Delft University of Technology

F.J.C. Immerzeel

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Abstract

For centuries sports are providing people entertainment and physical fitness. Often sports go hand in hand with competition. Olympic Games are organized every two years and the whole world is watching it. A crucial part of the competition is sports timing. A lot of people do sports and sport events take place on a large scale. Mass sport events attract over more than hundred thousand people and they all want accurate sport timing. This thesis focusses on analyzing the UHF RFID system used for mass sports timing, e.g. marathons. As of today UHF systems are commonly used in other industries, but are not optimized for sports timing. The main advantage of the UHF RFID system is the low cost of the individuals RFID tags used. Mass sporting events on a grand scale have contributed to the popularity of the UHF RFID systems. However, there are several sports timing specific challenges. Four major challenges can be identified: throughput, accuracy, missing detections and multiple antennas. There are several relationships between these challenges, e.g. there is a trade-off between accuracy and throughput. Optimized for throughput the system would attempt to read as many unique tags as possible, decreasing the probability of missing an athlete. In this situation the number of 'hits' (the number of times an athlete is seen by the system while crossing a timing line) is low, making it difficult to record the precise starting or finishing time. An optimized reader algorithm is proposed. The algorithm dynamically finds a good balance between throughput and accuracy.

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As a result, the optimized reader algorithm switches faster to the next antenna and misses fewer athletes. Simulations of marathon races show that the proposed optimized reader is more efficient, has more hits and misses fewer athletes than the currently used standard UHF RFID reader.

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Chapter 1

Introduction

For centuries sports are providing people entertainment and physical fitness. Often sports go hand in hand with competition. Olympic Games are organized every two years and the whole world is watching it. A crucial part of the competition is sports timing. A 100 meter sprint race has to be timed very accurate and for multiple people. World records are run with only a difference of hundreds of a second. A lot of people do sports and sport events take place on a large scale. Mass sport events attract over more than hundred thousand people and they all want accurate sport timing. How is it possible to time so many people for example running a marathon or cycling a race? This thesis focusses on this part. Now a day mass sports events use RFID chips to identify the individual runners. RFID chips are common used in other industries. Is it possible to optimize these standard RFID systems for sports timing, for example to obtain a more precise finish time? In the first chapter the fundamentals of RFID systems are explained. Secondly, varying sports timing systems are discussed and the challenges where they are dealing with. At last an optimized UHF RFID system is proposed and analyzed, especially for sport timing.

Chapter 2

Radio frequency identification (RFID)

Radio Frequency identification (RFID) is in the world of automatic identification gaining more and more popularity. For varying industries and for a lot of applications RFID is the ideal solution to automatically identify and to capture data. For recent years automatic identification systems are used. Similar technologies like bar codes and smartcards cannot be imagined without nowadays. Where bar codes caused a revolution in the 70's, it has now been replaced by RFID. RFID is a generic term for all the technologies that use radio waves for automatically identification of objects or people. The most knowable application for RFID is supply chain monitoring. Pallets or individual goods are tracked as they move along the supply chain. But also applications like toll collection and contactless payments, animal tracking, airport baggage tracking logistics, access management in offices, retail stock management and sports timing use RFID.

In this chapter a general introduction of RFID is given. First a brief historical overview of RFID is presented. Secondly various different categories of RFID are explained. After that the two most common used types of RFID, LF and UHF, are explained more deeply. And last a general introduction to the protocol used in UHF RFID is given.

2-1 History and technology background

The origin of RFID can be traced back to the World War II. During World War II the development of RADAR was significant, provoked by the war advances in using radio for the detection and tracking of airplanes. Under the head of Watson-Watt the British army designed an Identify-Friend or Foe (IFF) system which was used by the allies for identification of friendly aircrafts. Aircrafts began broadcasting back when they received a signal from the radar. Because they broadcast back they could be identified as friendly aircrafts. Since RADAR uses radio waves and detects objects, it can be seen as one of the first RFID system. One of the earliest papers exploring RFID is published in 1948 by Harry Stockman and is named 'Communication by Means of Reflected Power'. In this paper he represents a point to point transmission where the receiver generates the carrier power and the transmitter

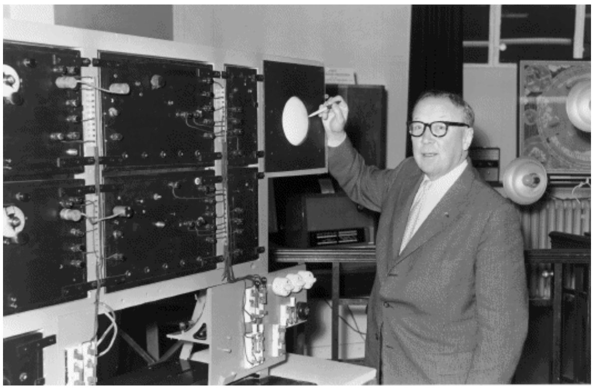


Figure 2-1: Watson-Watt (source:RFID Journal)

reflects a modulated signal. He presented a concept which would eventually become RFID. In the paper he also predicted that 'considerable research and development work has to be done before the remaining basic problems in reflected-power communication are solved, and before the field of useful applications is explored.' And he was right. It took almost thirty years before the real commercial RFID explosion took place and useful application became reality. The development of the transistor, the integrated circuit, the microprocessor and improvements of communication networks were necessary before the RFID could made a step forward.

The first commercial application of RFID is the Electronic Article Surveillance (EAS) and is in the name of the companies Kongo, Sensormatic and Checkpoint. These companies developed anti-theft equipment. The systems were using detection tags with only one bit representing the presence or absence of the tag and were used in retail stores to secure high value items and clothing.

The 1980's became the decade where the wide spread implementation of RFID applications took place. Commercial applications entered this decade the mainstream. Europe was focusing on animal tracking systems and toll roads. Roads in Norway, France, Spain, Italy and Portugal were equipped with automatic toll collection systems. In America the Association of American Railroads (AAR) and the Container Handling Cooperative Program (CHCP) were using frequently RFID equipment. Research and development continued in the 1990's. The size and the power usage of the tags reduced and the functionality of RFID expand. More and more commercial applications entered the market. The increase in commercial use requested standardization. International Standards Organization (ISO) and the International Electrotechnical Commission (IEC) published the first standards. RFID became part of the daily life.

You may ask why it takes over 50 years for the RFID technology to become mainstream. The main reason is costs. RFID is not as cheap as traditional labeling technologies like barcodes. It took 50 years of research and development before the cost decreased below the critical price point where it would be adopted by the large scale industries like for example consumer retail goods. What is achieved during decades of development? Nowadays the tags are reduced in size from a bread loaf to a size of sand particle. Price of the cheapest tag is now 5 cent. More than 2 billion tags are sold each year and tags can be read from a distance up to 200 meter.

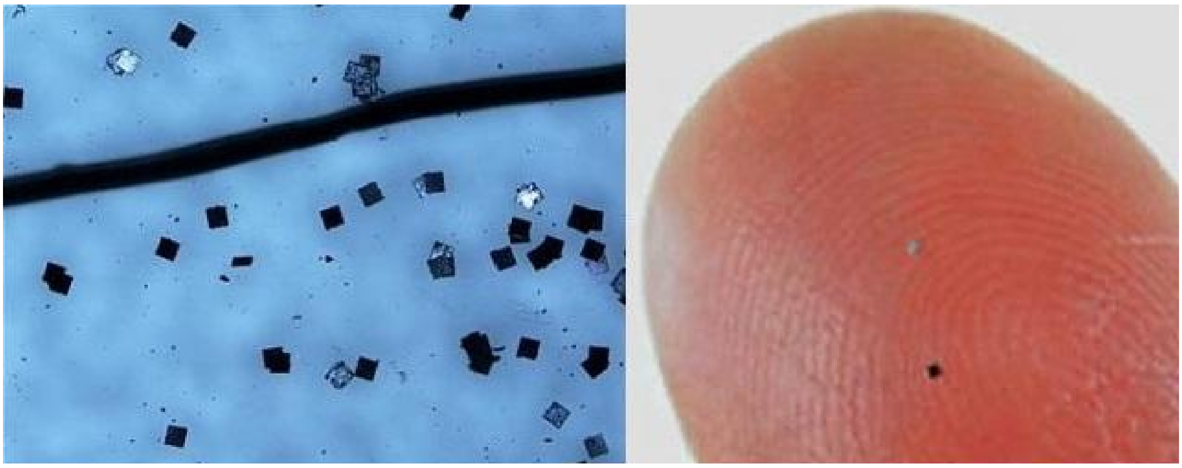


Figure 2-2: The smallest tag, 0.05 x 0.05 mm, compared with a human hair. (source:Hitachi)

2-2 RFID principles

What exactly is RFID? In general RFID is a term for technologies and systems that use radio waves to automatically identify people or objects. RFID is characterized by two main properties. The first one is that the data exchange between the data-carrying device and the reader is achieved without contact, using magnetic or electromagnetic fields. Secondly, it is used for identification. These two properties distinguish RFID from other identification systems like smartcards, barcode systems, optical character recognition and biometric procedures. A RFID system has two main components: the transponder and the reader. The transponder, called tag, is attached to an object which needs to be identified. The reader, or sometimes called the interrogator, reads the data from the tag and depending on the application it can write as well. Sometimes a third component, a controller, is added to the system. Depending on its application the controller handles the information read from the tag by the reader. RFID systems are available in varying sorts and types, all with different properties and with corresponding advantages and disadvantages. In the next sections the major difference criteria's of RFID are given. The operating frequencies and its associated reading ranges, the differences between active and passive tags, coupling methods and at last different ways of data processing are explained.

2-2-1 Frequency and Range

One of the most important distinction criteria of a RFID system is its operating frequency. Many system properties are related to the operating frequency. Two important parameters the operating frequency affects are the reading range and the coupling type or in short the way the reader communicates. How the frequency affects the reading range and de coupling type a little bit of knowledge about electromagnetic physics is required. Let me give a short introduction in electromagnetic fields. Around a sending antenna an electromagnetic field is formed. This field is split in two areas, namely near-field and far-field. Near-field is the region close to the source, the sending antenna, and far-field is the region further away from the antenna. How the electromagnetic field reacts is very different in both fields. Hence, the way the RFID reader communicates with a tag is different in near-field and far-field. In near-field the RFID reader makes use of magnetic induction, where on the other hand in far-field it makes use of electromagnetic (EM) wave capturing. The near-field area ranges from source to a distance of one wavelength. The far-field starts approximately two wavelengths from the antenna and extends outwards. Between near- and far-field there is a transition zone. Since wavelength is equal to the light speed divided by the frequency ($\lambda = \frac{c}{f}$, where $c \approx 3 \times 10^8$), the way the RFID systems communicate is affected by its operating frequency. At low frequencies wavelengths are big, sometimes up to more than 2 kilometer. This means that at near-field RFID-systems work well with low frequencies. Due to the small wavelengths of high frequency waves, far-field RFID systems are operating with high frequencies.

There are four frequency bands where RFID systems are operating at, classified as Low Frequency (LF), High Frequency (HF), Ultra High Frequency (UHF) and Super High Frequency (SHF) or sometimes specified as microwave. RFID is emitting in these frequency bands:

- LF: 125 KHz - 134 KHz
- HF: 13.56 MHz
- UHF: 860 MHz - 960 MHz
- Microwave: 2.45 GHz and 5.8 GHz

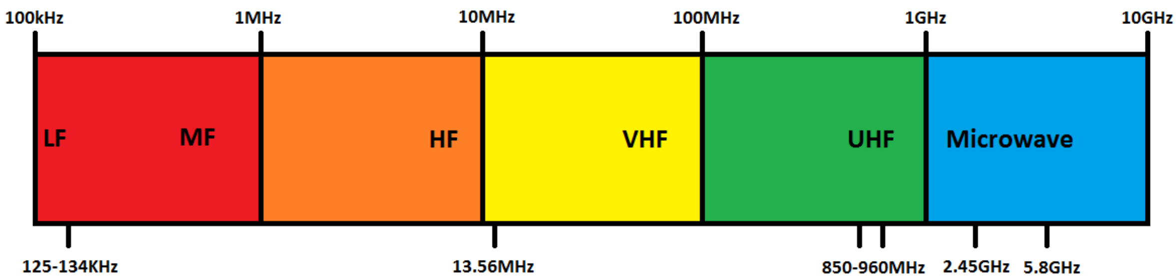
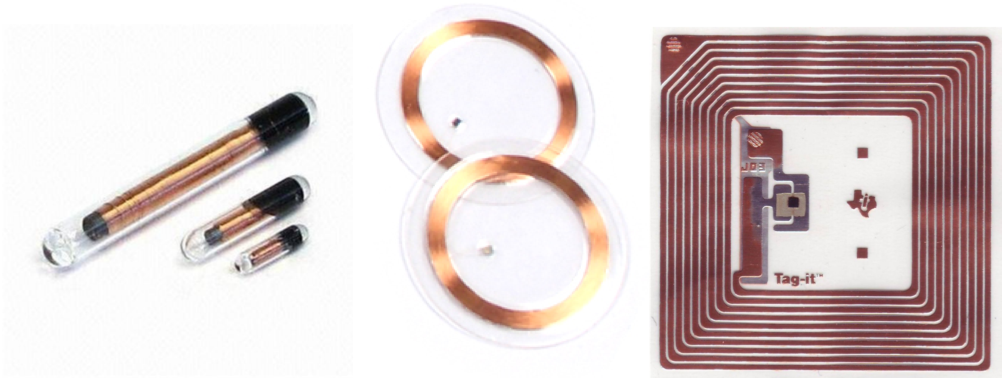


Figure 2-3: RFID frequency spectrum

2-2-2 Coupling types

Electric, magnetic and electromagnetic fields are used for physical coupling between tag and reader. The distance between reader and tag determines the coupling type. Three types are defined: *close coupling*, *remote coupling* and *long-range*. Close coupling systems have, like its name already indicates, a close distance between tag and reader. Close coupling RFID systems are able to communicate at a distance up to 1 centimeter. De advantage of close coupling is that it provides a greater amount of power from reader to the tag, so also microchips with non-optimal power consumption are able to communicate. RFID systems with a range up to 1 meter are called remote coupling systems. Both systems, close - and remote coupling, are operating in the near-field area of the antenna. This means that they use the lower frequencies, LF and HF, as carrier frequency. Faraday's principle of magnetic induction is the basis for the coupling between reader and tag in near-field. Both reader and



(a) LF glass tube **(b)** LF disk **(c)** HF label

Figure 2-4: LF and HF coil tags (source:Texas Instruments)

tag have an antenna coil. Figure 2-4 shows some RFID tags with magnetic coupling, where the coils are good visible. The reader passes an alternating current through the readers coil and the coil generates a magnetic field. A smaller tag coil located in the field reacts on this magnetic field and induces an alternating voltage across its coil. This alternating voltage is rectified and connected to a capacitor. A charge reservoir accumulates. Eventually the tag microchip can be powered up when enough charge is collected. Each time the tag draws energy from the magnetic field this leads to a voltage drop at the readers coil. This principle is used by the RFID system to communicate. The tag sends binary information by switching on and off a particular load. The reader detects this by different voltage drops. This is called *load modulation*. Advantage of load modulation is that the tag is able to communicate while receiving power. Figure 2-5 presents a schematic overview.

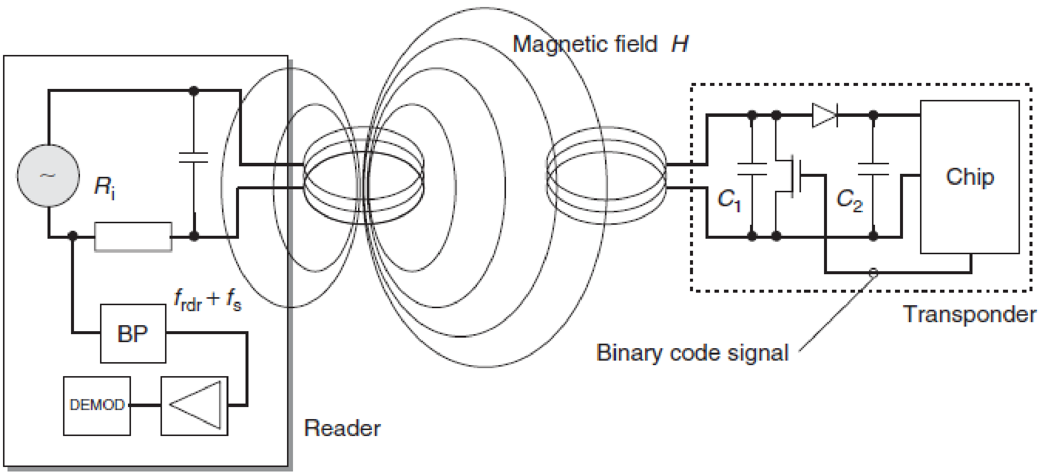


Figure 2-5: Inductive coupling for LF and HF (source:Finkenzeller [1])

The term for communication where tag and reader are sending and receiving at the same time is *full-duplex* (FDX). The equivalent of full-duplex procedure is *sequential* (SEQ) communication. During sequential communication the reader and tag do not transmit at the same time. The reader has radiating periods and listening periods. Only during listening periods tags respond to the reader. So first the reader transmits data and powers up the tag. After the transmitting period it enters a listening mode. During listening mode tags are able to transmit their data to the reader. An advantage is that transmitting signals from the reader and tag do not disturb each other. A crucial disadvantage is that tags do not receive radio wave energy during transmitting. This requires that tags need to have a battery or capacitor, big enough to have power during the transmitting period.

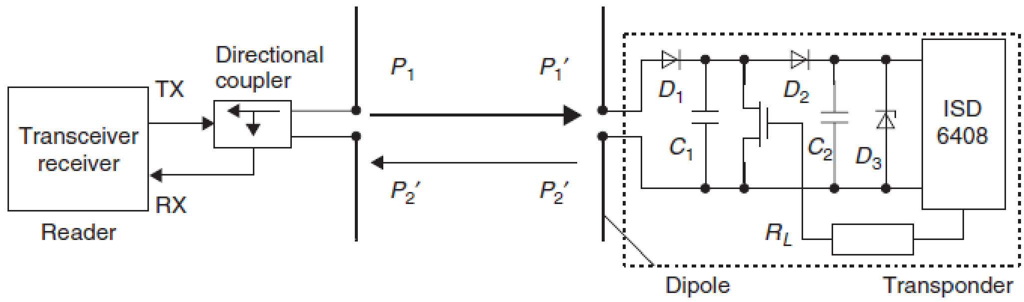


Figure 2-6: Backscatter for UHF and Microwave (source:Finkenzeller [1])

Where close- and remote coupling systems takes advantage of the near field of the antenna, long range systems makes use of the far-field. This means that long range systems operate at the higher frequencies, UHF and Microwave. Electromagnetic (EM) waves travel from the reader's antenna and are captured by the tag antenna, which is most of the time a dipole antenna. The EM waves induce an alternating potential difference across the arms of the dipole. Like the magnetic field in near field systems is able to deliver energy to the tag, exactly the same principle occurs for UHF and Microwave tags. The alternating potential from the EM wave is rectified and charge accumulates in the capacitor. After some time the microchip will power up when enough charge is collected. However, the long range tags are beyond the near-field range, so information can not be transmitted back to the reader using load modulation. Instead of load modulation, far-field systems use the backscatter principle. Let me explain this. A schematic view of backscattering is shown in Figure 2-6. A dipole antenna, which is most of the time used in long range tags, can be designed with precise dimensions such that it is tuned for a particular frequency. At this frequency most of the energy is absorbed by the antenna. However, when the impedance of the antenna changes then the characteristics of the antenna also change. At that moment the antenna absorbs not all the energy, but reflects part of the energy back. A high sensitive receiver is able to read the reflected energy. Near field systems makes use of this principle. To communicate the tag changes its impedance over time, representing a logical one or zero. A high sensitive reader antenna reads the reflected signals and translates it to logical ones and zeros. In practice, the detuning of the tag is done by placing a transistor across the dipole arms and then switching it on and off. Figure 2-7 shows some far-field dipole tags.

A third and less common used data transfer method is Surface Acoustic Wave (SAW). SAW does not make use of microchips, but makes use of a physical process called the piezoelectric effect. SAW tags look more like barcodes and have stripes to store their unique idea. Figure 2-8 shows a basic layout for a SAW tag. SAW operates, just like backscattering, in the far-field area of the antenna. EM waves arrive at the dipole antenna of the SAW tag. An

(a) Dogbone tag **(b)** Alien tag

Figure 2-7: UHF label tags (source:UPM Raflatac, Alien Technology)

electroacoustic transducer converts these electromagnetic waves into acoustic surface waves. Surface waves travel along the piezoelectric substrate surface till they arrive at vertical stripes. These stripes reflect an acoustic wave back to the transducer. This phenomenon can be seen as a wave in a pool traveling from one side of the pool to the other side. Halfway the pool there is a flexible wall, which reflects part of the wave and passes the other part through. Further on there is another flexible wall, also reflecting and passing through. At the beginning of the pool all the reflected waves arrive at different time stamps. The time between is correlated with the distance between the walls. Exactly the same occurs on the surface of the tag. Reflected acoustic waves arrive at the transducer at different timestamps, depending on their distance, and electromagnetic waves are transmitted back from the tag to the reader with a correlated time in between. The reader converts these timestamp into a unique idea. This principle can be seen as a wireless RFID readable barcode where a unique pattern represents a unique id.

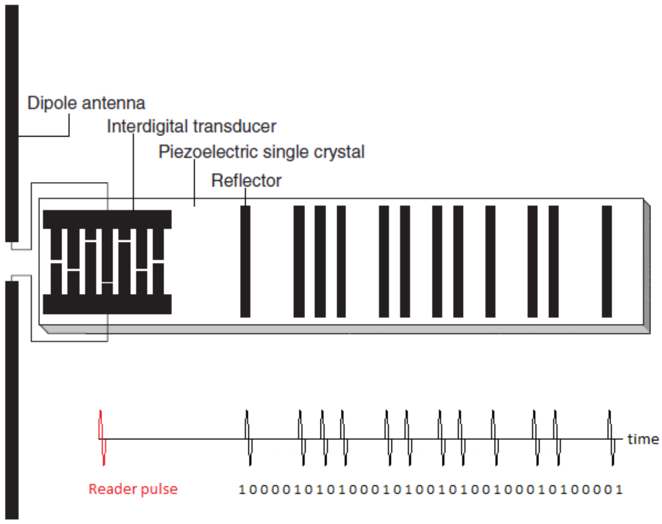


Figure 2-8: SAW tag (source:Finkenzeller [1])

2-2-3 Active and Passive tags

In previous sections is explained that tags are energized by the magnetic- or electromagnetic field. These tags are called passive tags. Besides passive tags, there are also active tags.

Active tags require a power source. They use power stored in a small integrated battery. This leads to higher cost and bigger sized tags. The tags lifetime is also limited by the stored energy. However, active tags have one big advantage. They do not need a strong field to be energized. This increase the communication range dramatically. Active tags exist which can communicate up to 100 meter. Unfortunately most active tags still need a readers UHF field to modulate and transmit back and are able to communicate up to 15 meter. Another advantage is that the microchips in active tags stay powered when the tag is outside the field. Tags are able to stay in a certain state or are able to do more power consuming actions, for example difficult security or encryption operations or memory write operations. Nevertheless, RFID tags are often used for mass usage. Tag price is in most application crucial and passive tags are in this case more attractive.

2-2-4 Liquids, Metals and Human body

Many common materials have a negative effect on the performance of a RFID system. Nearby water or other wet surfaces and metal affects the impedance of the antenna. Since antennas are optimized for certain frequencies, a change in impedance decreases its performance. LF and HF signals are better able to penetrate water than UHF and Microwave signals. High frequency signals are more likely to be absorbed by liquid than lower frequencies. A human body contains a large amount of water and is therefore an excellent absorber for RF signals. Metal is an electromagnetic reflector and RF signals are not able to penetrate through it. A piece of metal between tag and reader or metal in the environment has bad effects on the performance of a RFID system. Both low and high frequencies have worse performance. Nevertheless perform lower frequency systems better than higher frequency system in de area of metal and liquids.

2-2-5 Antenna nulls and orientation

Due to antenna nulls and orientation of electromagnetic waves, it is possible that tags are not able to communicate with the reader. Antenna nulls are spots where a tag will not receive the electromagnetic wave. Figure 2-9 shows the radiation pattern of a dipole antenna. A dipole antenna radiates and receives electromagnetic waves in a doughnut pattern. This means that dipole antennas radiates towards and receive signals from all directions except the direction along the conductor. Since most of the time UHF tags have dipole antennas, these tags will not be detected by the reader if the tag is orientated in the same direction as the field. Null spots or weak signals can also occur by detuning of a tag, for example when multiple tags are placed near each other or the tag is nearby materials with a high dielectric permittivity like metal or liquids.

Besides the null spots, detection problems can also occur due to polarization of the electromagnetic field. Electromagnetic waves are horizontally, vertically or circular polarized when they radiate from the antenna. If the electromagnetic waves are horizontally or vertically polarized, then the orientation of the tag is crucial. When the dipole antenna tag is placed in the same direction as the polarization, then it receives the electromagnetic waves. If the tag is placed perpendicular to the polarization it will not receive any wave. Figure 2-10 shows this principle. When the field is circular polarized, then the tag orientation is less import but it can receive only half of the transmitted power.

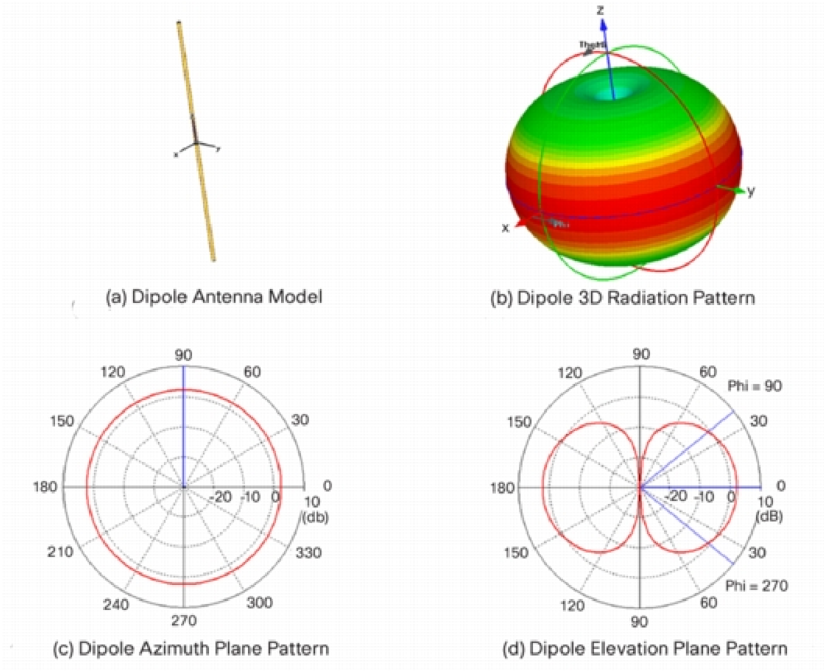


Figure 2-9: Magnetic field of a flat coil (loop antenna) (source:Cisco)

LF and HF tags have loop antennas. Loop antennas are coils and this means that the orientation is dependent on the magnetic field lines. Figure 2-11 shows the magnetic field of a coil. If the receiving loop antenna is placed in such a way that magnetic field lines of the transmitting loop are able to penetrate the coil plane, then the orientation is right. The more lines penetrate, the more current is flowing through the coil. If no lines penetrate, then there is no signal and it can be seen as an antenna null. Best signal is found when maximum field lines penetrate. This happens when two coils are placed on top of each other. Figure 2-12 shows good orientation examples.

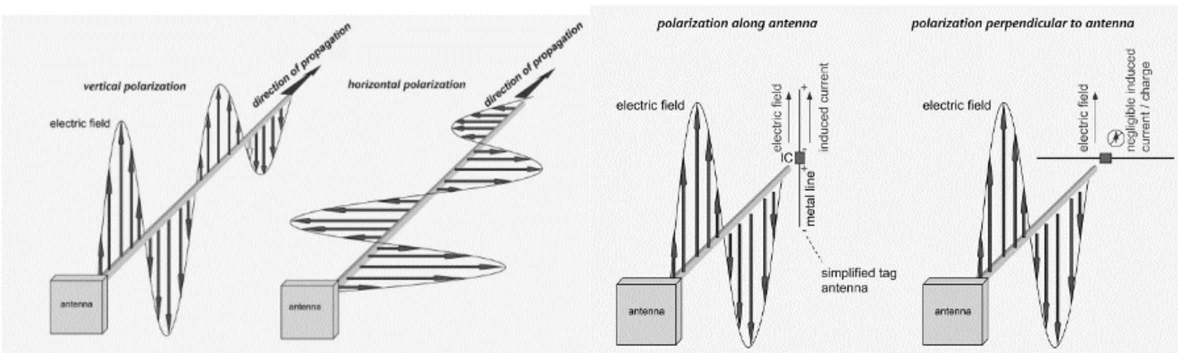


Figure 2-10: Polarization principle of EM-waves (source: rfid.net)

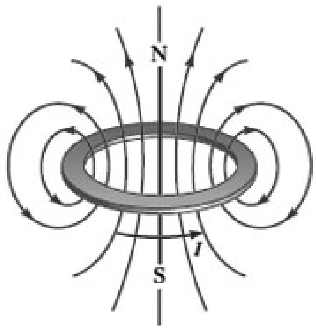


Figure 2-11: Magnetic field of a flat coil (loop antenna) (source: h2physics.org)

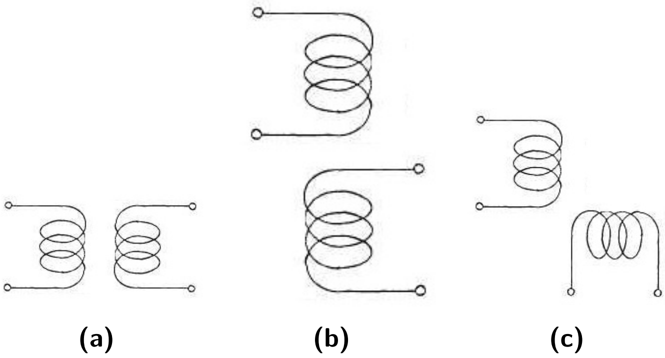


Figure 2-12: LF and HF tag orientation

2-2-6 Data rates

Data rates are defined by the operating frequency. The higher the frequency, the faster the data rate can be. For a LF system you can think of a data rate in the order of Kbps. Microwave systems can reach a data rate up to Mbits per second. Typical bit rates are RF/8, RF/16, RF/32, RF/40, RF/50, RF/64, RF/80, RF/100 and RF/128. This is determined by how many carrier pulses present one logical bit. The data coding technique tells in what manner these pulses present a bit, further on in the RFID protocol section there are a few of these data coding techniques explained.

2-2-7 Overview

In this section are the basic and most common techniques used in RFID systems explained. Clarified is how the frequency influences the characteristics of the system. The way the environment and the chosen antennas properties influences the readability of the tag is explained and the range and speed at which the RFID system operates are described. An overview is given at Table 2-1.

	Frequency band	Read Range	Power supply	Coupling	Benefits	Drawbacks
Low Frequency (LF)	125 - 134 KHz	10 cm up to 70 cm	passive	inductive	Works better with water and metal	Short read range and slower data rates
High Frequency (HF)	13.56 MHz	20 cm up to 100 cm	passive	inductive		
Ultra High Frequency (UHF)	860 - 960 MHz	3 m up to 10 m	passive	backscatter	Long range, high data rate and cheap tags	Works bad with water and metal
		up to 100 m	active			
Microwave	2.45 and 5.8 GHz	3 m	passive	backscatter		
		up to 200 m	active			

Table 2-1: RFID types overview

2-3 RFID protocol

In every form of communication a set of rules and formats has to be followed in order to exchange information. The set of rules and formats is called a protocol. Protocols describe among others the communication medium, the coding and modulation of the data, the structure and the meaning of the data.If a RFID reader and tag comply with the same protocol, then they are able communicate. Protocols are arranged in different abstraction levels. RFID protocols are standardized by the EPC Global and the International Standards Organization (ISO). These standards describe the RFID protocols according to the OSI (Open Systems Interconnection) model in two abstraction layers, the physical layer and the MAC (data) layer (see Figure 2-13). In the next two sections is described which RFID protocols are common used at the physical layer and which are used in de MAC-layer.

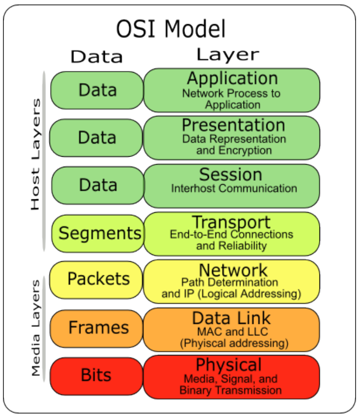


Figure 2-13: OSI model

2-3-1 Physical layer

The physical layer declares the electrical and physical specification. For example line encoding, modulation and data rates are specified by the physical layer protocol. The transmission medium plays an important role in the specification of these protocols. In RFID the transmission medium is Radio Frequency (RF). RF is split in LF, HF, UHF and Microwave. Since different frequencies segments do not have the same characteristics, there are different protocols for line coding and modulation. There are three digital modulations for RF: Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK) and Phase Shift Keying (PSK). In Figure 2-14 are these digital modulation signals drawn. Like the name suggests, ASK varies the amplitude to make a difference between a logical zero and one bit. The simples form is On-Off Keyring (OOK), where a zero bit is presented by a flat line and a one bit by the carrier signal. FSK difers the frequency and PSK changes the phase to differentiate between a zero and a one bit. A combination between digital modulations is also possible, for example to present multiple bits in one period. Quadrature Amplitude Modulation (QAM) is an example of this. It varies the phase and amplitude to present a set of bits. An example is drawn in Figure 2-15. In the physical layer is often besides the modulation also a line coding used, optimized for a

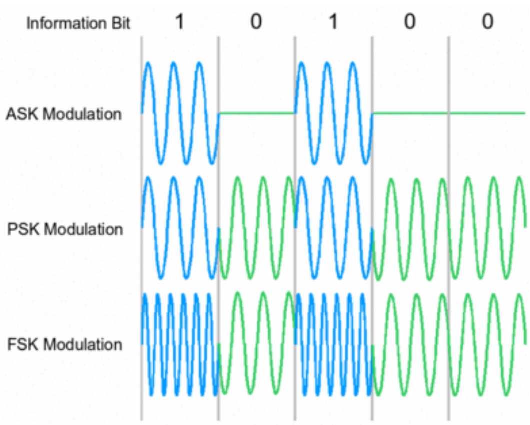


Figure 2-14: Digital modulations

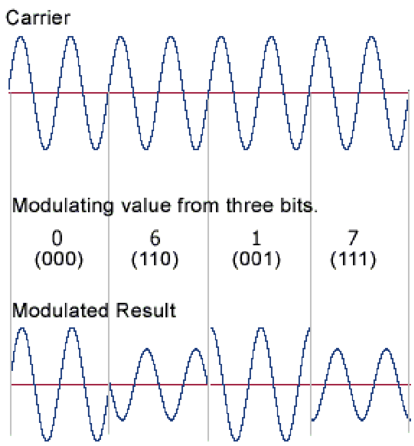


Figure 2-15: Example of 8QAM (source:Computer Desktop Encyclopedia)

specific transmission link. Special encoding patterns present a digital value. There are a lot of line encoding techniques. To gain a clear understanding what exactly line coding is, an example is given in Figure 2-16. The example shows a Pulse Interval Encoding (PIE). The widths of the logical one signal in ASK (duty cycle) presents a zero or a one bit. Line coding is used to get a more robust transmission line, optimally tuned for the used transmission medium.

2-3-2 MAC layer

The Media Access Control (MAC) layer is a sub layer of the data link layer (see Figure 2-13). It controls the communication for multiple access networks. RFID systems have most of the time multiple tags and only a few readers. Collisions occur when multiple tags try to talk with

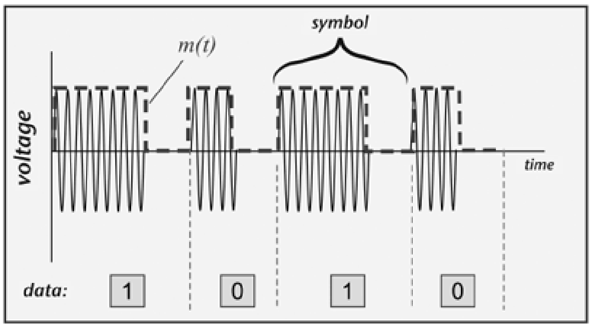


Figure 2-16: Pulse Interval Encoding combined with ASK (source:M. Dobkin [2])

the same reader at the same time. The MAC-protocol handles the traffic for multiple access networks. You can think of medium channel access and addressing mechanisms. Basically they can be categorized in two classes: deterministic protocols and stochastic protocols. The main difference of these classes is the way they try to avoid collisions and the way they handle access control if multiple tags try to communicate at the same time. Where deterministic protocols use predefined priorities for tags, make stochastic protocols use of randomness. This means most of the time that deterministic protocols follow a tree traversal algorithm. RFID tags form a binary tree arranged by their identifier and the reader explores the tree in a systematic way. Stochastic protocols use framed slotted ALOHA (FSA) or an equivalent protocol. Frame slotted ALOHA use randomness to reduce the probability of collision. For example each tag generates a random number telling them in which time slot they have permission to talk. Both deterministic and stochastic protocols have been included in RFID standards. And overview of the most common RFID standards arranged by their frequency are given in Table 2-2.

125 kHz	**13.56 MHz**	**860-960 MHz**	**2.45 GHz**
ISO11784/5,14223 ISO18000-2	ISO14443 (MIFARE) ISO15693 (Tag-IT) ISO 18000-3	EPC Class 0 EPC Class 1 EPC Gen 2 ISO18000-6	ISO18000-4 Intellitag μ-chip

Table 2-2: RFID standards overview

2-3-3 EPC Global Class 1 Gen 2 protocol

The EPC Class 1 Gen 2, or in short 'Gen2', is the most recent protocol for UHF RFID Systems. This protocol plays an important role for UHF Sport timing systems. An in depth description is therefor given.

Physical layer

The signaling interface between the reader and the tag may be viewed as the physical layer [3]. The signaling interface includes *operating frequencies, modulation, data coding, RF envelope,* *data rates* and other parameters that deal with the RF communication.

The Gen2 prescribes that the operating *frequency* is between 860 MHz and 960 MHz. Nevertheless, the local radio regulations and the local frequency environment determine at which frequency the system may operate. For example *European regulations* [4] allow only transmissions in the 865.6-867.6 MHz band. Four 200 KHz bands are available and a reader may transmit with a maximum power of 2 Watt ERP. If a reader does not hop between those four frequencies and only uses one channel, then it should stop transmitting for at least 100 milliseconds after 4 seconds. For the *United States* the Federal Communications Commission (FCC) rules and regulations are the decisive factor. According to these FCC rules transmissions are allowed in the 902-928 MHz band. Fifty 500 KHz channels are available, but readers are obliged to use Frequency Hopping Spread Spectrum (FHSS). This means that the carrier frequency (channel) switches every 400 millisecond. The maximum radiated power is 4W (EIRP).

Three kinds of *modulation* may be used by the reader to communicate with the tags: Double Side Band-ASK (DSB-ASK), Single Side Band-ASK (SSB-ASK) and Phase Reversal-ASK (PR-ASK). Tags are able to demodulate all three modulation types. The reverse communication, from tag to reader, can be done using ASK or PSK modulation. The modulation type is selected by the tag vendor. Readers needs to be able to demodulate both ASK and PSK.

The *data coding* from reader to tag is always *Pulse Interval Encoding* (PIE). The power down time for a data-0 is with PIE quite small. The tags are powered by the reader and a shorter power down time is therefore an advantage. A long power up pulse represents a data-1 and a short power up pulse represents a data-0. The duration of a data-0 is called a Tari. A data-1 should have a duration of 1.5 to 2 Tari (see Figure 2-17). Tags use different data coding's to backscatter their signal: *FM0* or *Miller*. The reflected data signal is quite low and noise plays a more important role. Depending on the noise, a different data coding can be used to obtain more reliability. FM0 inverts the phase every symbol boundary and for a data-0 an extra inversion is made in the middle of a symbol. Miller only inverts its phase between two data-0's and in the middle of a data-1 symbol. Miller symbols can have different lengths, depending on the noise. The longer the symbols are, the more samples can be made and the more reliable is the transmission. Miller-2 and Miller-4 are shown in Figure 2-19.

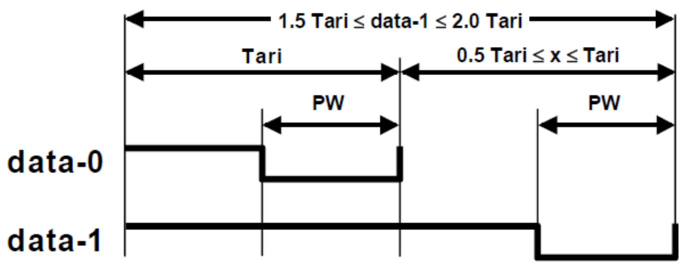


Figure 2-17: Pulse Interval Encoding (source: EPC Global [3])

Data rates are defined by the carrier frequency and the data coding. For example the Tari duration and the Miller size affect the data rate. Data rates are announced before each transmission by a preamble. The device that is transmitting determines the data coding and rate by transmitting a preamble before transmitting the data package. Down-link rate from

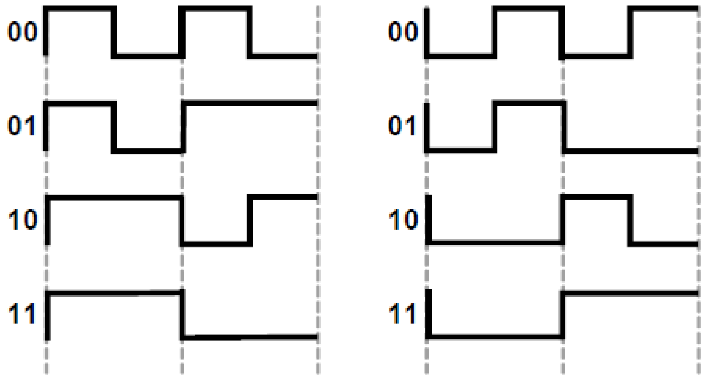


Figure 2-18: FM0 sequences (source: EPC Global [3])

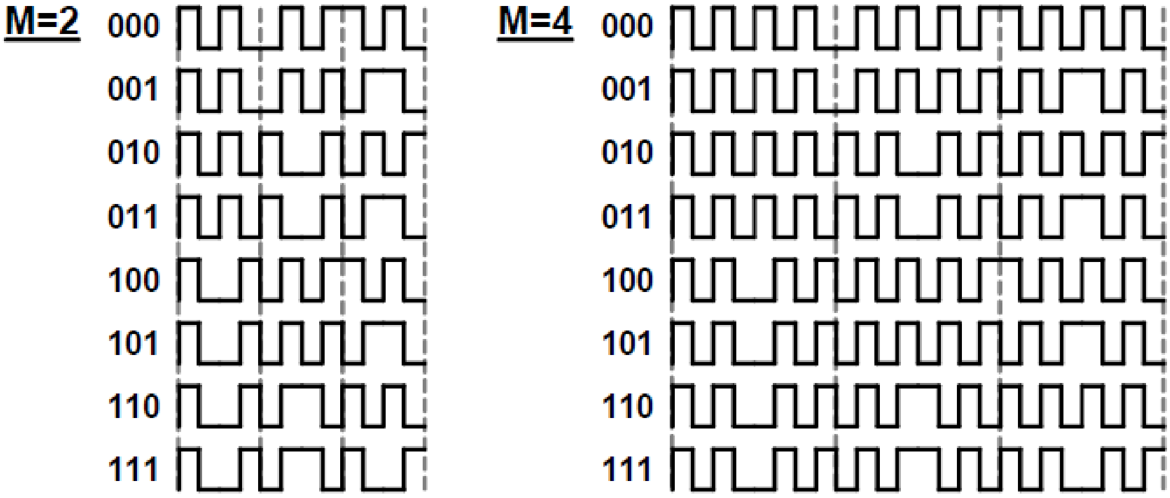


Figure 2-19: Miller-2 and Miller-4 sequences (source: EPC Global [3])

26.7 kbps to 128 kbps can be achieved [5] and an up-link data rate from 5 kbps to 640 kbps [3].

Anti-collission protocol (MAC layer)

The Gen2 protocol specifies also how to handle with multiple tags trying to access a single reader. The anti-collision protocol used has a stochastic approach. It follows the idea from the framed slotted ALOHA protocol. Each time frame has 2^Q slots, where Q is an integer in the range (0, 15). Depending on the expected number of tags the reader defines a Q and thus a number of slots. Each tag generates a random number between 0 and $2^Q - 1$, which reflects the timeslot it starts sending its data. If multiple tags generate the same random number, they start sending at the same time and collisions occur. Resending the data is then possible in the next frame, when the tags generate a new random number. Due to the randomness, tags are eventually able to send the data. If too many collisions occur in a frame, then the Q number is too low and may be incremented in next frame. If a frame has too many empty slots, then the Q number may be reduced to obtain smaller time frames. An optimum is found when number of slots is set equal to the number of tags [6].

Reading the tags starts with managing the tag population. A *Select* command reduces the number of responding tags by selecting a part of the tag population. Only tags that comply with the requirements in the select command will respond. A new inventory round (frame) is announced by the *Query* or *QueryAdjust* command. Using the Query command, new tags can be introduced. The QueryAdjust command only starts a new inventory round without introducing new tags. The Query command contains, among others, the number of time slots in the inventory round and the selection properties. The tags which comply with the selection properties and take part in the frame generate a random slot number between 0 and $2^Q - 1$ and will send their data in the generated time slot. A new time slot is announced by the *QueryRep* command.

Tags can have two states, A en B, presented by the inventoried flag. A default tag start in state A. A tag makes the transition from state A to B or vice versa if it is read correctly or if it is forced by the Select command. A reader is free to use the Query, QueryAdjust and QueryRep commands at any time. For example it can start a new inventory run with a Query command during an unfinished time frame. A good example of using both states to obtain a lot of readings is as follow. A reader sends a Query command. An inventory round starts and visible tags can be read. Tags that are read in the first round are now in state B. A new round is started using QueryAdjust, but no new tags are invited and tags which failed in the first round will now be read in de second. This can continue till all tags are in state B. The number of slots can be decreased each round to obtain smaller round times. A new inventory round can be started with reading tags in state B. After reading all tags in state B, the reader starts again reading tags in state A. This alternating reading method accomplish that tags are read multiple times, for example to obtain a reliable timestamp when tags pass a timing line. The more a tag can be read during crossing a timing line, the more accurate passing time can be calculated.

Selection tag populations A reader may choose to not inventory all tags within the range. Tags can be selected to form a population of tags which can be read or ignored during inventory. With the *Select* command the Selection Flag (SF) or one of the inventoried flags can be assert or deassert. Each tag has four inventoried flags. Each inventoried flag has two values, state A and state B. The purpose of the inventory flags is that the tag supports sessions. Each session has one inventory flag. Two or more readers are then able to communicate time-interleaved with a common population of tags, without interrupting each other. The select command contains the parameters: Target, Action, MemBank, Pointer, Length, Mask and Truncate. Target and Action indicates whether and how the SF or the inventoried flags should be modified and in case of the inventoried flags, for which of the four sessions. The other parameters indicate which part of the memory bank of the tag should correspond to be considered for selection.

Inventorying tag populations The inventory command set consists of *Query*, *QueryAdjust*, *QueryRep*, *ACK* and *NAK*. An inventory round starts with a Query command. The Query command sends information about the Q-factor, the data coding for the tag to reader communication, the session number and whether the selected population should be read or ignored. A successful read procedure during a single time frame is given in Figure 2-20. The following steps are taken for a successful read:

1. Tags generate a time slot number. If this number is zero, the tag backscatters a random 16-bits number (RN16).
2. The reader will echo the RN16 as an acknowledgement
3. The tag will backscatter the data: Protocol Control (PC) + Electronic Product Code (EPC) + 16-bit Cyclic Redundancy Check (CRC16)
4. The reader announce a new slot (QueryRep), a new round (Query or QueryAdjust) or let the tag know that the received data is not valid (NAK). A tag inverts its inventoried flag in case of a succesful read.

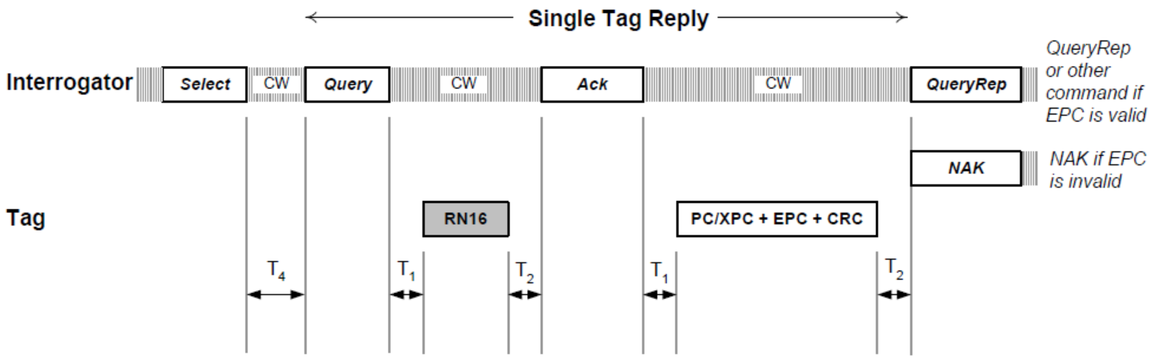


Figure 2-20: Single tag reading procedure (source: EPC Global [3])

All tags participating in the round decrement their slot number after a QueryRep and if the slot number is now zero the whole procedure starts again. A round stops after 2^Q timeslots. A reader can also interrupt a round before finishing by starting a new round, using the Query command. Tags that fail with communication during their time slot will get a new change in the next round. How does the protocol react on collisions, empty slots or lost communications between tag and reader? These situations are given in Figure 2-21. If two or more tags have generated the same slot number, then collisions may occur. Both tags backscatter a RN16. In this case the reader will not send an acknowledgement, but announce a new slot (QueryRep). If no tags respond after a QueryRep (empty slot), then the reader will start a new slot after a timeout period. In case of a lost connection, tag does not respond, the reader also starts a new slot after a timeout period.

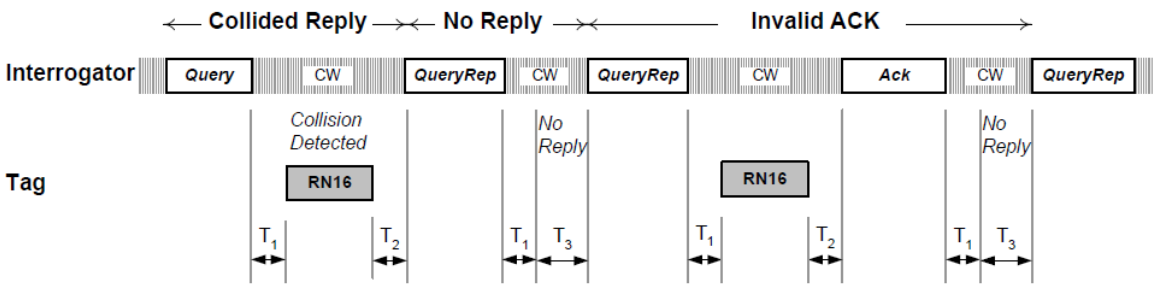


Figure 2-21: Procedure for collissions, empty slots and lost connections (source: EPC Global [3])

Accessing individual tags After acknowledging of a tag, a tag may be accessed for further operations. Commands like *Erase*, *Kill*, *Lock*, *Read*, etc. can be executed. For sports timing are these commands not used. The only operation taken on the tag during sports timing is reading the tags unique identification number. This number is encrypted in the EPC memory and is read during a normal single reading operation. Therefore no further commands are necessary and these commands will not be discussed in this thesis.

Chapter 3

Sports timing

3-1 Introduction to sports timing

For centuries sports are providing people entertainment and physical fitness. Often sports go hand in hand with competition. Olympic Games are organized every two years and the whole world is watching it. A crucial part of the competition is sports timing. A 100 meter sprint race has to be timed very accurate and for multiple people. World records are run with only a difference of hundreds of a second. A lot of people do sports and sport events take place on a large scale. Mass sport events attract over more than hundred thousand people and they all want accurate sport timing. How is it possible to time so many people for example running a marathon or cycling a race? This chapter will answer this question. Three different sport timing systems are shown. Known weaknesses of these systems are identified and challenges for sports timing are given.

Figure 3-1: How accurate should sports timing be?

3-2 Timing systems

In this section three mass sports timing systems are shown. These systems are developed by MYLAPS Sport Timing. This company develops innovative sports timing products for different kind of sports. For example the big events like Formula one, Indy Cars, NASCAR and the Olympic Games are timed with their products. But also smaller events, like speed skating, marathons and for the Dutch people, if there would be an Elfstedentocht this year, then it would be timed with MYLAPS timing equipment.

The three mass sport timing systems explained in this section are based on RFID technology. Chapter 1 gives a general introduction to RFID technology. The first system has the name ChampioChip. It makes use of passive tags and operates in the Low Frequency (LF) range. Besides a LF system, a newer Ultra High Frequency (UHF) system is shown called BibTag. A third system, ProChip, has active tags and is more used in professional series. Detailed information of these systems is given in the next sections.

3-2-1 ChampionChip (LF)

ChampionChip is a LF RFID sports timing system. Each athlete wears a chip with a unique identification number. Mats are placed at timing lines, for example at a start line and at a finish line. If an athlete crosses the line and runs over the mat, then the chip code of the chip worn by the athlete is read by the system. Readers are constantly reading chip codes of athletes running over the mats and timestamps are stored in combination with the chip codes. Subtracting the finish timestamp with the starting timestamp gives the total sports time. What exactly happens when an athlete crosses a timing line? To explain this I will first introduce all the components of the ChampionChip system: the Ear, the Controller, the detection mat and the ChampionChip.

Detailed part is removed (Confidential)

3-2-2 Pro chip (Active)

The ProChip system is like the ChampionChip a RFID system. Again the system registers all athletes that cross a timing line and multiple lines are used to calculate the total sports time. But instead of a passive tag for the ChampionChip system, the ProChip is an active tag. This means that it has a battery onboard and it does not need to be energized before it is able to send its unique identification number. Due to the onboard power supply the ProChip is much cleverer than the ChampionChip and is therefore able to get a much more accurate passing time. *Detailed part is removed (Confidential)*

3-2-3 Bibtag (UHF)

The third system and most recent designed system is the BibTag system. It is characterized by its ultra-high operating frequency. For this reason the BibTag system has a longer reading range, faster communication between tag and reader and a different type of antenna. The tag, with the corresponding name BibTag, is flat and really cheap. This makes it attractive for mass sports events. The BibTag is most of the time a disposable and is stuck to the number bib. No extra registration is required to link a personal tag to a start number. This is an important selling point and why mass event organizers more likely prefer BibTag instead of ProChip or ChampionChip. Besides the extra organization and the price per tag, transport of a BibTag is also cheaper. It easily fits in an envelope.

Detailed part is removed (Confidential)

Reader protocol

The EPC Class 1 Gen 2, or in short 'Gen2', protocol plays an important role in the BibTag timing system. Standard tags are used due to their low cost price. Because the tags are standard, they comply with standardization. In this case, the BibTag sticks to the EPC Global Class 1 Gen 2 protocol. Also the readers in the decoders are standard UHF readers which again make use of the Gen2 protocol. The Gen2 protocol is quite flexible and allows users to set a lot of parameters to make it useful for a lot of applications. It has a high data rate, due to the Ultra High Frequency. The protocol is supposed to read up to 1800 tags per second in adequate environments [7]. It has a flexible physical layer. This is important for sports timing, because it can be used worldwide with different local Radio Frequency (RF) regulations (FCC, CEPT). Furthermore, it does support dense reader environments. The BibTag decoder can have multiple readers and because marathons are never on the same place, the noise varies per location. The protocol supports reliable signaling in environments with multiple readers and a lot of noise. Multiple encodings and modulations are supported, so an optimal configuration can be made depending on the application. The protocol makes continuous identification and simultaneous reading possible by using of inventory flags and sessions. This can be an advantage for sports timing, because the athlete and tag are moving and the more the tags are scanned, the more accurate passing time can be measured. To speed up the communication the protocol supports truncated transmission. Only parts of the tag memory can be read, for example if only the serial number of a fixed group needs to be read. At last the protocol supports CRC. This improves reliability. A description of the EPC Class 1 Gen 2 protocol can be found in the Section 'RFID Protocol'.

Chapter 4

Challenges for sports timing

4-1 Introduction

This thesis focusses on analyzing the UHF RFID system used for sports timing. As of today UHF systems are commonly used in other industries, but are not optimized for sports timing. The main advantage of the UHF RFID system is the low cost of the individuals RFID tags used. Mass sporting events on a grand scale have contributed to the popularity of the UHF RFID systems. Nevertheless there are some several sports timing specific challenges. This chapter describes these challenges in a detailed and explanatory manner. Four major challenges can be identified: throughput, accuracy, missing detections and multiple antennas. There are several relationships between these challenges, e.g. there is a trade-off between accuracy and throughput. Optimized for throughput the system would attempt to read as many unique tags as possible, decreasing the probability of missing an athlete. In this situation the number of 'hits' (the number of times an athlete is seen by the system while crossing a timing line) is low, making it difficult to recognize a pattern. Without the pattern the accuracy of the time registered when an athlete crosses the timing line is low. The purpose of this chapter is to describe how the system faces the challenges and to answer questions such as: "What is the maximum throughput the system could encounter in the field?" and "What is an acceptable accuracy?"

4-2 Throughput

The timing systems are used during mass sport events, which have experienced exponential growth the last couple years. This raises the following question: What is the maximum number of athletes that can physically cross a start line per second and is a standard UHF system able to read that many tags per second with an adequate accuracy? Currently this is unclear. Statistics of past events are available and a compact analysis is made in relation to throughput.

4-2-1 Emperical analysis

An empirical study gives us an overview in what order of magnitude we may think of. Of course these results are probably not the absolute maximum density that can be found in worst case. But at least it gives some information about the expected maximum density. Four events are analyzed:

- Valencia Marathon 2011
- Boston Marathon 2012
- AGU Egmond-Pier-Egmond 2012
- Amstel Gold Race 2012

Valencia Marathon

The Valencia Marathon had this year a very busy start on a bridge. In five minutes all 5866 runners crossed the starting line. So this event can be considered as a good event to find a maximum density. To get a good picture how the start was look like see Figure 4-2. The 5866 runners are only the runners on the bridge at the left side. The bridge on the right side was the start of a half marathon.

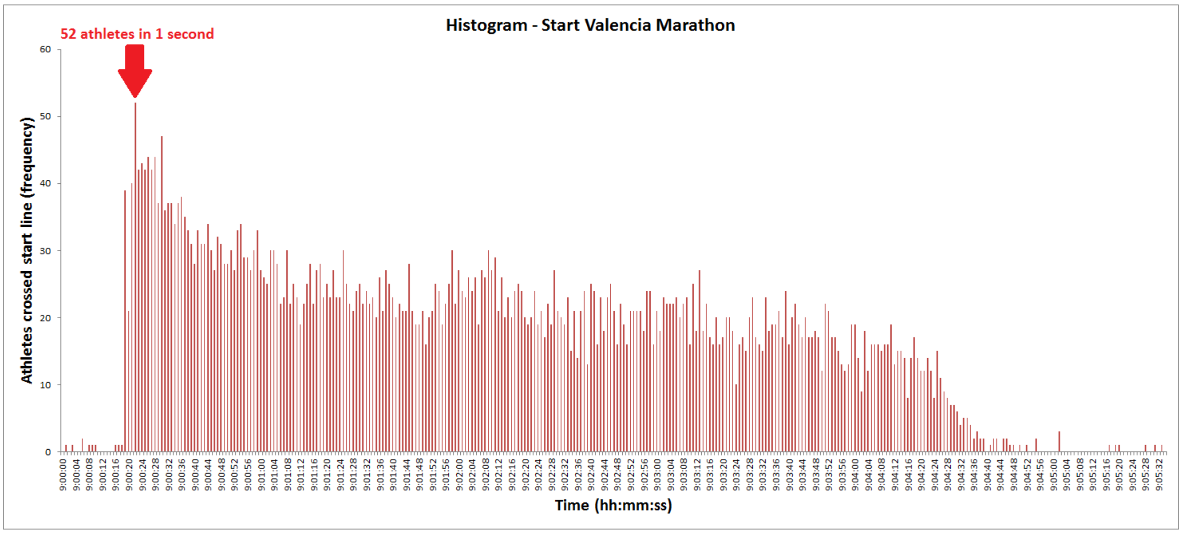


Figure 4-1: Number of unique athleses crossing the start line over time

Figure 4-1 shows the number of athletes that crossed the start line and are detected by the system each second during the start. The start was done by a gunshot at 9 o'clock. Interesting in this graph is the *peak of 52 athletes*, just a few seconds after the gunshot. This is the maximum throughput found during an event.

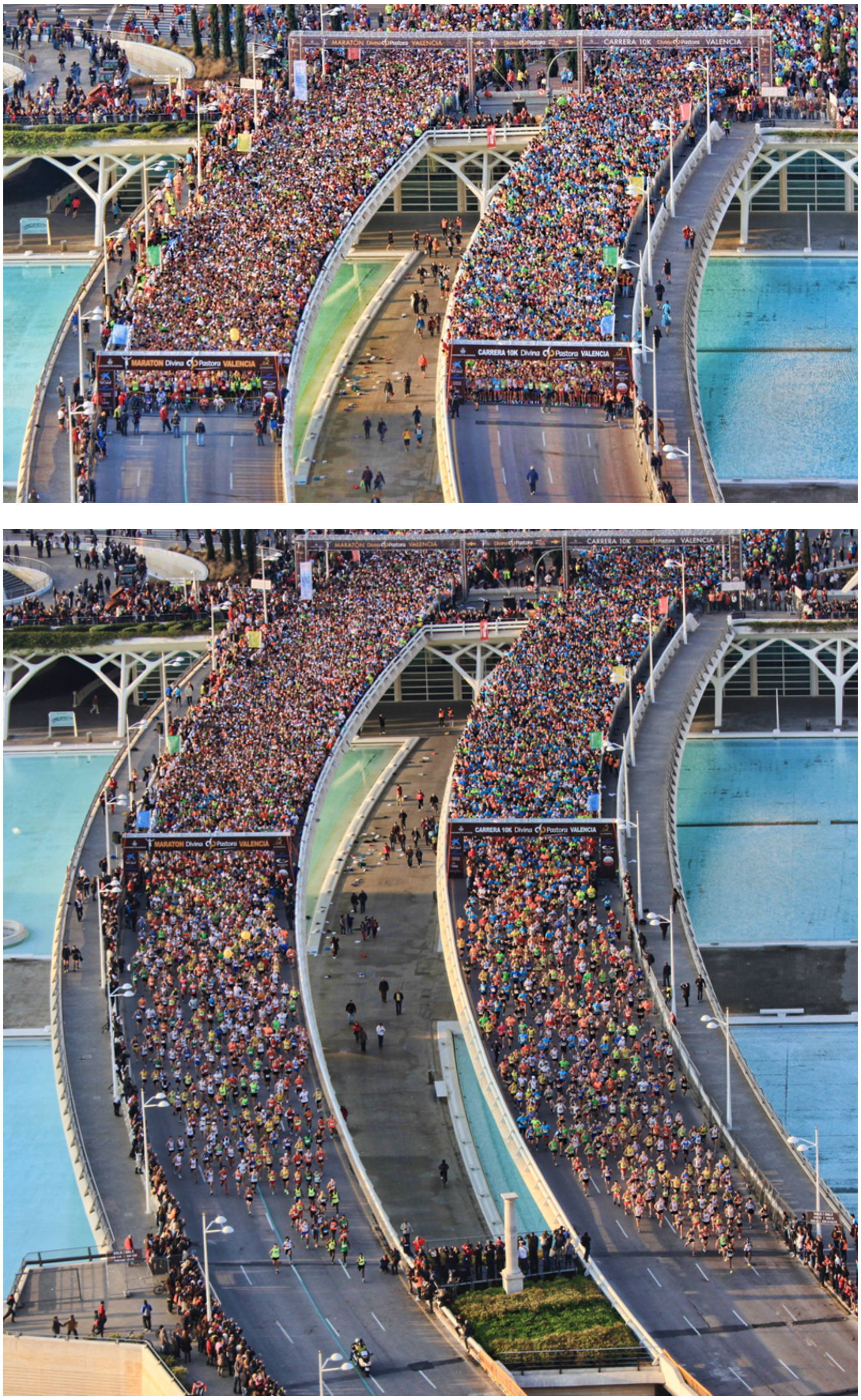


Figure 4-2: One of the busiest starts (Valencia marathon 2011) (photo:Hector Domingo & Sergio Corella)

Boston Marathon

The Boston Marathon is one of the most important marathons of the year. More than 25.000 athletes took part in this event. Results of the throughput analysis are shown in Figure 4-3. The maximum throughput during this event is found at the third race, right after the gunshot. A *maximum of 46 athletes* crossing the start line in one second is found.

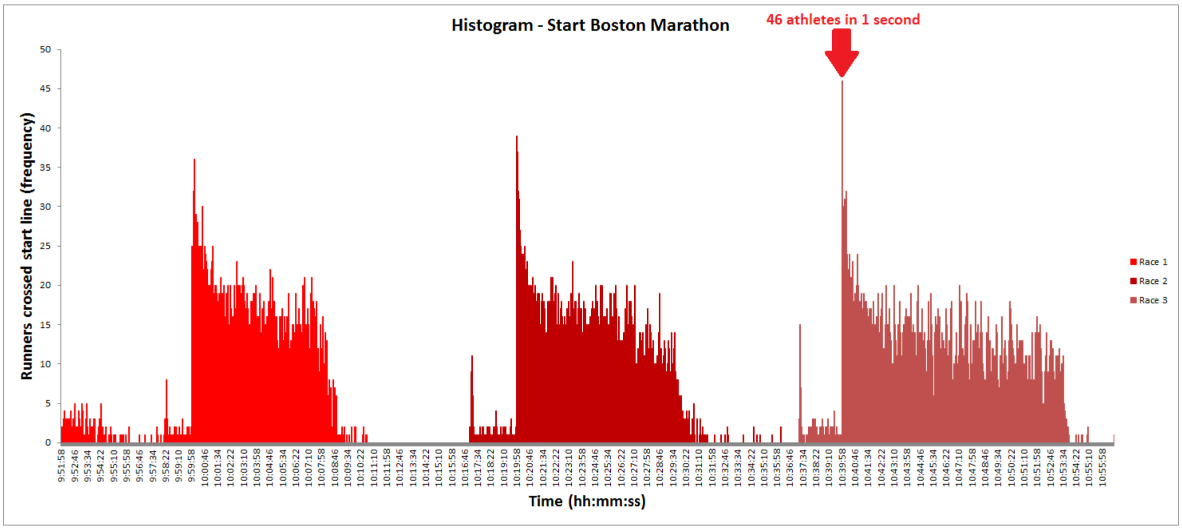


Figure 4-3: Number of unique athletes crossing the start line over time

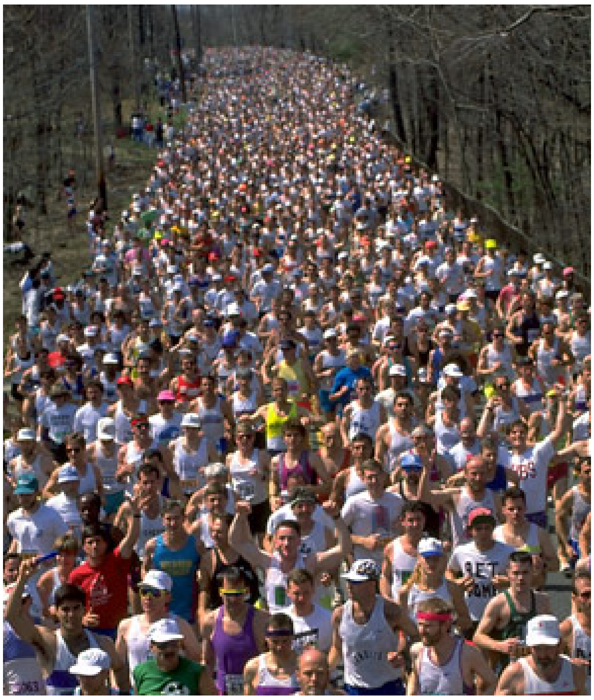


Figure 4-4: Boston marathon with more than 25.000 runners (source:Huffington Post)

AGU Egmond-Pier-Egmond and the Amstel Gold Race

The AGU Egmond-Pier-Egmond and the Amstel Gold Race are different than the Valencia and Boston Marathon. These events are not running events but cycling events. They are different in the way that starts are less busy, but have more speed. Because the athletes have more speed it is possible that the throughput is higher in spite of the lower density. For this reason both events have been analyzed for throughput. The AGU Egmond-Pier-Egmond is analyzed during the start situation. Because the speed is often higher after the start, the Amstel Gold Race is analyzed a few kilometers after the start. The density is then still high, but the speed is also higher than during the start. Results show that *the throughput during cycling events is far below the throughput during running events*. A maximum of 14 cyclists in one second is found during the AGU Egmond-Pier-Egmond and a maximum of 7 in one second is found during the Amstel Gold Race.

4-2-2 Conclusion

The results show that the highest throughput is found at running events. An overview of the empirical analysis is given in Table 4-1. In worst circumstances are 52 athletes crossing the line in one second. Standard Class 1 Gen 2 readers are able to read up to 1500 tags per second (at 640 kbps and FM0) [8] in the US and up to 600 tags per second in Europe (at 436 kbps and FM0). In theory 52 tags per second should be no issue to read all tags. However the amount of tags per second reduces when Miller encoding is used, when interference occurs and when more collisions occur. The UHF readers that are used in the BibTag system are setup with Miller4 and have a data rate of 320 kbps in Europe and 274 kbps in the US. A European reader is then able to read *up to 300 tags per second* and an US reader can read up to 270 tags per second. These readers are using a variant to Slotted Aloha with an efficiency of 37 percent [9]. The real value is therefore lower than 300 tags per second and approaches the 52 tags per second. Another issue is that multiple reads (hits) are necessary to obtain a reliable passing time. The more tags are in the reading field, the less accurate is the passing time.

Event	Start line width	Number of runners	Max. density (tags/minute)	Max. density (tags/s)
Valencia Marathon 2011 (running)	8 meters	5866	1426	52
Boston Marathon 2012 (running)	11 meters	25062	1316	46
AGU Egmond-Pier-Egmond 2012 (cycling)	8 meters	2681	431	14
Amstel Gold Race 2012 (cycling)	8 meters	13284	92	7

Table 4-1: Overview of an empirical analysis of the throughput

4-3 Accuracy

4-3-1 Introduction

With accuracy is meant the time registered by the system and the actual time that the athlete crosses the timing line. The registered time can be earlier than the actual time, but also later. To be able to distinguish between two athletes who start or finish just a short period apart, the accuracy is crucial. A distinction is made for the professional athlete and the leisure athlete.

Professional athlete

For the professional athlete does the International Association of Athletics Federations (IAAF) rules describe that the time results should have *a resolution of 0.1 second* [10]. This means that the system is able to separate athletes who finished 0.1 seconds apart. However, the final result should be recorded to the whole second. Professional athletes always start with a gunshot or another start signal. Not the actual time that the athlete crosses the start line is applied, but the time of the start signal. This is called the gross time. As a result is the resolution of only the finish line the decisive factor. Finishes with professional athletes are with *low density*. Since density (number of tags in the field) is correlated with accuracy, and a lower density means higher accuracy, this is a benefit.

Figure 4-5: Low density finish for professional athletes (source:shutterstock.com)

Leisure athlete

Leisure athletes use the *net time*, because most of the time the gun shot is already passed if they cross the start line. This means that the times of each athlete of both the start line and the finish line count. The worst case deviation (time between actual time and registered time) should be taken twice to obtain the worst case accuracy of the whole system. However, accuracy is less important for the leisure athletes. For example a resolution of 1 second is in most cases more than enough.

4-3-2 Analysis

Basic idea

An accuracy test is done to get clear how accurate the BibTag system is. Chosen is for an empirical approach to envelop all influencing parameters. A lot of parameters play a roll, for example the influence of the human body, the impedance change of the antenna when stepping on the mat, number of tags in the field, etc. To obtain the precise passing time a finish camera is used (Figure 4-8). This is a high speed camera with 10.000 lines (frames) per second, normally used in the Formula 1 and for ice skating. The camera has an accuracy of 0.1 milliseconds. It works as follow. From every photo only the vertical pixel lines focusing on the finish line are taken. These pixel lines are plot on a horizontal time axis. This gives a stationary picture of a moving object. An example is given in Figure 4-6. The time obtained by the finish camera is compared with the time registered by the BibTag system. The difference between the finish camera time and the registered time is the error. The errors are measured for a sufficient number of runners and the obtained result are plot to give an idea of the inaccuracy of the BibTag system.

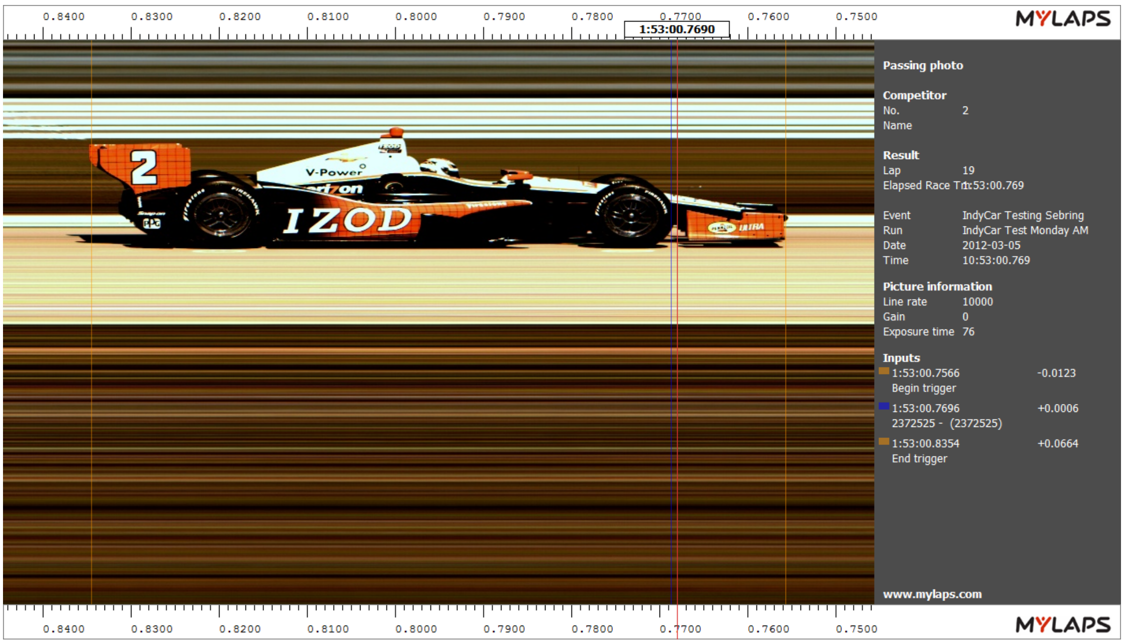


Figure 4-6: Example of a finish camera photo (source: MYLAPS)

Test setup

Two events have been visited to obtain the test data, the 'Loyalis NK Veldloop gemeenten 2012' and the 'Zandvoort Circuit Run 2012'. A picture of the setup is given in Figure 4-7. At this event the line camera and the BibTag system were positioned 50 meters before the official finish line (Figure 4-9). The timing line has four antennamats which are connected to a European BibTag system. During the second event the same test is done but this time with eight antennamats. The line camera is positioned at the top of the MYLAPS logo, in the middle of the antennas (red line). The line camera and the BibTag decoder are both synced to GPS to have exactly the same time. They are connected via an Ethernet network to a laptop to store all the data.

Figure 4-7: Test setup

Figure 4-8: Line camera (source: MYLAPS)

Figure 4-9: Test system was positioned 50 meters before official finish

Example

An example of the data obtained by the line camera and the BibTag system is given in Figure 4-10. The red pixel line where the athletes bib starts presents the exact finish time measured with the line camera. In the same picture is also the time drawn where the BibTag system registered the passing. These are the blue and green lines. The time between the finish camera and the BibTag is the error of the system.

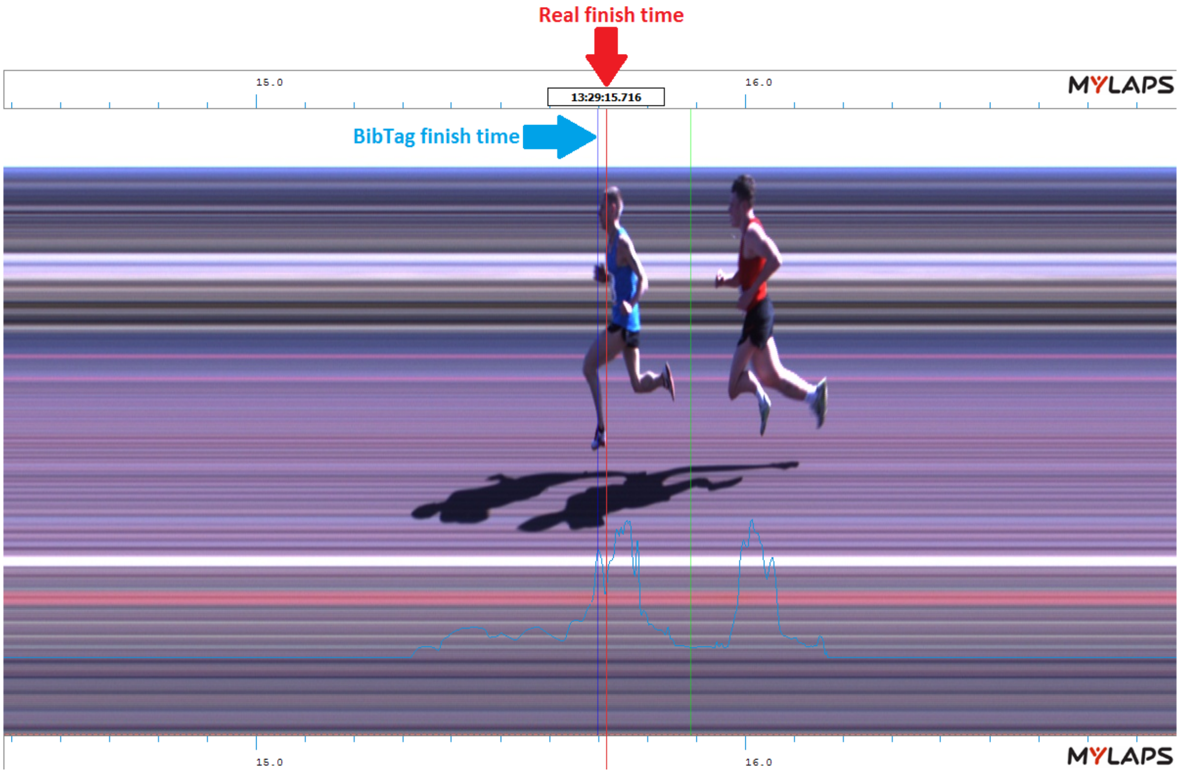


Figure 4-10: Example of test data recorded by the finish camera and BibTag system

Results

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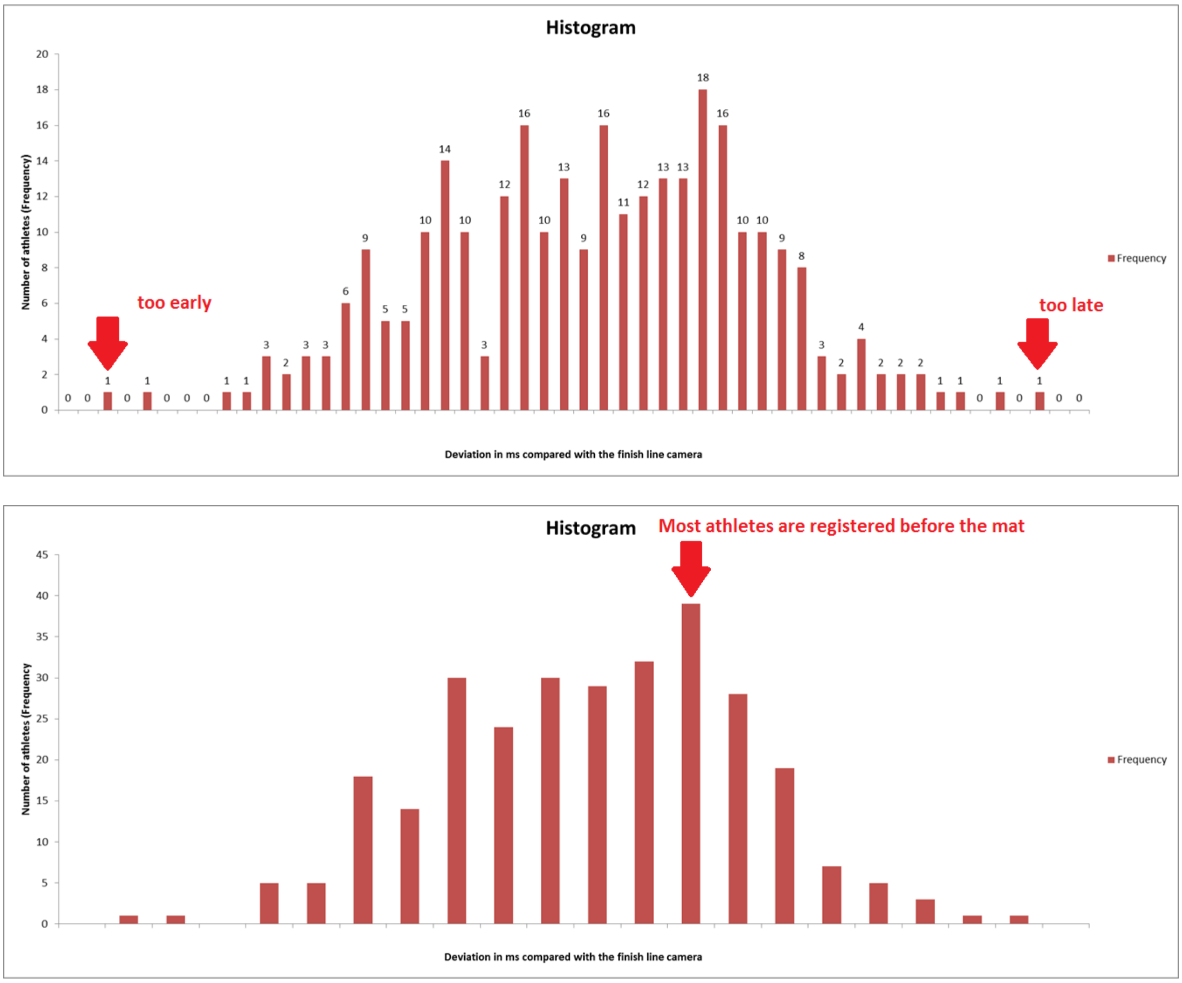
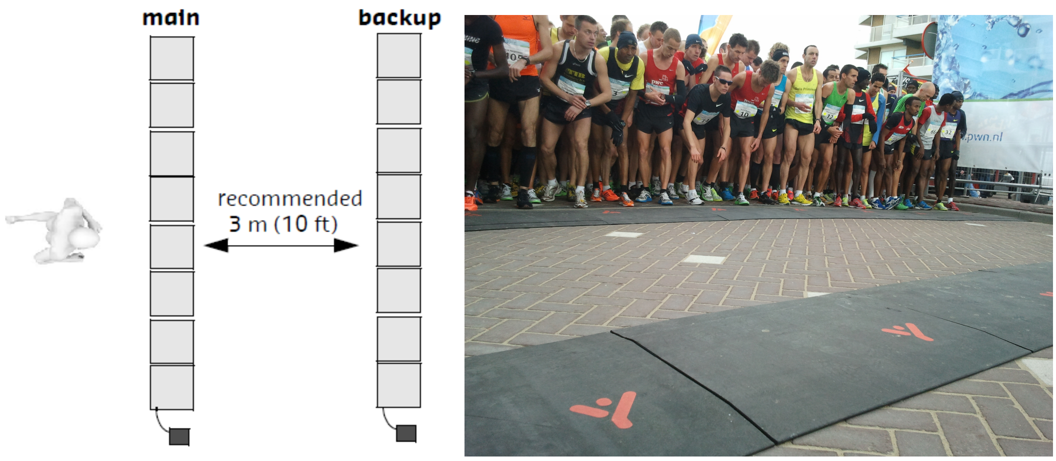


Figure 4-11: Time difference between the BibTag system and the actual finish time

4-4 Missing detections

One of the most critical requirements of a timing system is that the athlete must always be detected. If the passing time is missing, then the athlete does not have a recorded time. There will not be a second change. In addition, if an athlete is not detected then the rest of the results are also not right. For example if the winner is not detected, then the system will show that the number two finished first, the number three finished second and so on. Therefore missing detections have a high priority.

There are ways to reduce the probability that an athlete is not detected. For example it could be reduced by placing two systems near each other. If one fails to detect an athlete then the second will probably not miss. The probability that two systems both fail at the same time is lower than the probability that one system fails. The BibTag system makes uses of this principle. A start and finish have normally two timing lines. A main line and a backup line are placed, three meters apart (Figure 4-12). If the main line misses the athlete, then the recorded time of the backup line is taken. Another way to reduce missing detections is by placing a video camera. Recovering of the finish time can then be done afterwards by hand. However, the best situation is the one with only one system that will always detect the athletes and other systems are placed for redundancy. This means that if one system for example powers down then the second is able to take it over.



(a) (b)

Figure 4-12: Two timing lines at the start and finish to reduce the probabilty of missing an athlete (source: MYLAPS)

4-4-1 Missing detections due to antenna reception

Most missing detections occur due to the wireless transmission. Three examples of these kind of problems are shown in Figure 4-13. Figure 4-13a shows an athlete who did not place the BibTag on the chest. The orientation of the tag in this picture is different than when the tag was correctly placed on the chest. Due to the polarization of the antennamat and the wrong orientation of the BibTag, the reception of the wireless signal is in this case bad and the athlete could be missed by the system. Figure 4-13b shows a runner who is stepping on the antenna, which is placed in the mat. While a foot is placed on the antenna, it is detuned. The strength of the backscattered signal from the BibTags is received weaker than normal and may cause a missing detection. The third picture (Figure 4-13c) shows a common problem at the start and finish. Often athletes press the start or stop button on a watch. Hands then cover the antenna of the BibTag. Another situation is that a tag sticks to the body of a wet (sweat/rain) person. The human body can detune the antenna and absorb a subtantial part of the received or transmitted power. These problems are all antenna related. In this thesis antenna problems will not be discussed. The thesis focus is mainly on the wireless protocol.

(a) Wrong placed tag **(b)** Foot detunes antenna in mat **(c)** Hand covers tag

Figure 4-13: Missing detections due to bad antenna reception (source: MYLAPS)

4-4-2 Missing detections due to the reader protocol

In the previous sector is described that the BibTag system could have two series of mats, a main line and a backup (Figure 4-12). The main- and backup lines have different protocol setups. The main line tries to detect every tag as much as possible, so multiple hits per athlete. The backup line is optimized to detect every tag once, so only one hit per athlete. Therefore is the main line more accurate than the backup line. The hit with the strongest backscattered signal is the recorded time. If only one hit is received, the it is possible that this hit is received meters before the line or after the line. With more hits, the recorded time is the one closest to the antenna. Statistics show that the *backup lines performs better for detection* than main lines. Backup lines have often more detections than main lines at high density or equal number of detections if the density is low. Because a backup line only reads each BibTag once it has more time to read new BibTags in the field. New BibTags with bad antenna signal will then not be overpowered by already detected Bibtags. The statistics are given in Table 4-2. The start of the Valencia Marathon 2011 had this year a high density. The backup line had in this case 97.4 percent of the athletes detected, where the main line only had 93.4 percent.

	Start				Finish			
	Main	Backup	Both	Density	Main (drop-out corrected)	Backup (drop-out corrected)	Both (drop-out corrected)	Density
Valencia 2011 (Marathon)	5722 93.4%	5964 97.4%	5989 97.8%	High	5697 96.9%	5769 98.1%	5796 98.6%	Low
Madrid 2011 (Marathon)	12361 97.9%	12434 98.5%	12548 99.4%	Medium	-	-	12210 99.7%	Low
Boston 2012 (Marathon)	22015 97.5%	21944 97.2%	22423 99.3%	Medium	21453 98.9%	21466 98.9%	21609 99.6%	Low

Table 4-2: Athlete detection performance are different for main and backup lines

Besides missing detections it is also important to have enough hits of each athlete to obtain an accurate passing time. Where the backup system performs better for detection performs the main system better on the number of hits. A good balance should be found to have *enough hits (accuracy) without missing athletes*. Figure 4-14 shows how many hits the BibTag system (main line) has during a start and a finish. Remarkable is that there are a lot of BibTags with a low number of hits during start. This is caused by the high density during a start situation. The number of athletes in the field is then high. Also does the figure show a correlation between the strongest signal and the number of hits. The number of hits is correlated to the quality of the receiving signal.

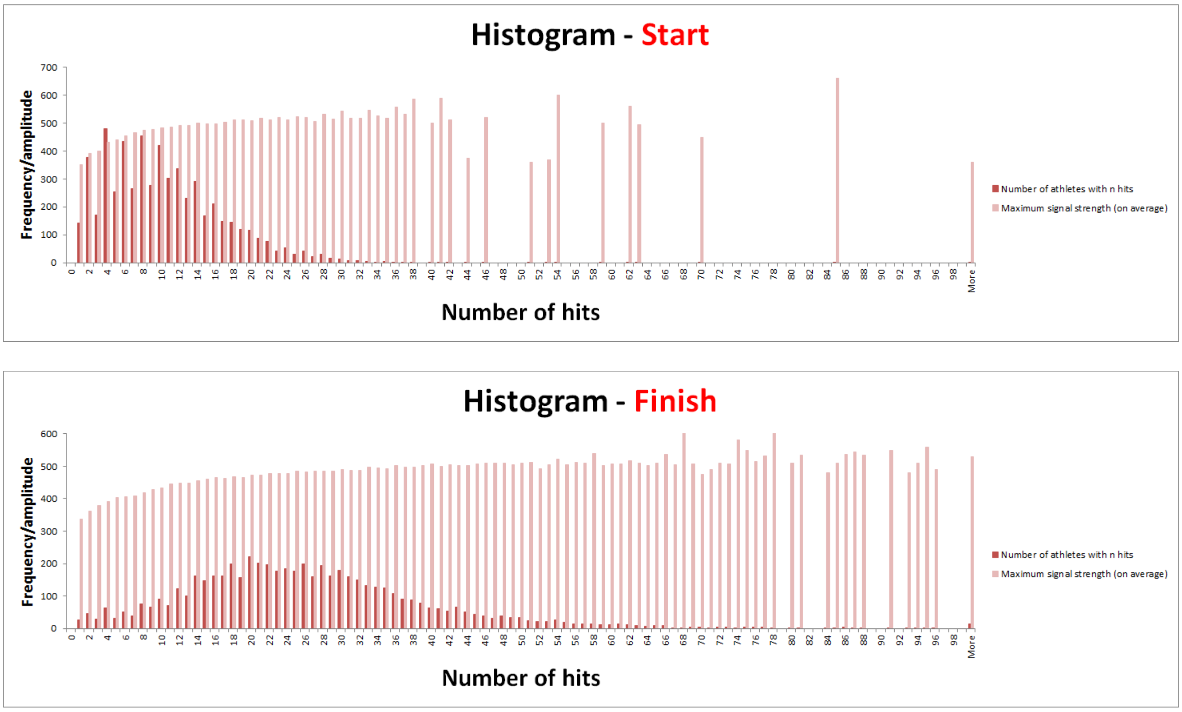


Figure 4-14: Number of hits per athlete and the correlated maximum signal strength (on average)

4-4-3 Missing athletes due to government regulations

Different countries have specified regulations for radio transmissions. These regulations may influence the radiation time and bandwidth. The UHF bandwidth around the European Union is regulated by ETSI. It states that four 200 kHz channels are available for maximum transmission (2 Watt ERP). Furthermore it says that after at most 4 seconds the reader may not transmit for at least an uninterruptible period of 100 milliseconds. This may be an issue for sport timing. If the reader is *not able to transmit for at least 100 milliseconds*, then the accuracy may decrease and athletes could be missed.

An option is to apply frequency hopping. When frequency hopping is applied, then within 4 seconds the reader should hop to another channel and no break is required. In the past was Listen Before Talk (LBT) necessary. The break period or frequency hop was therefore obligated so that other devices were also able to transmit. LBT is now abolished, but the break is still there. Currently the European BibTag system has fixed channels and frequency hopping is not implemented. An inaccuracy or athlete miss may occur due to the 100 millisecond transmission timeout. This timeout period is shown in Figure 4-15. The United States (US) region has no problems according to the FCC rules. It has fifty 500 kHz channels and frequency hopping is already implemented. It has not a timeout problem.

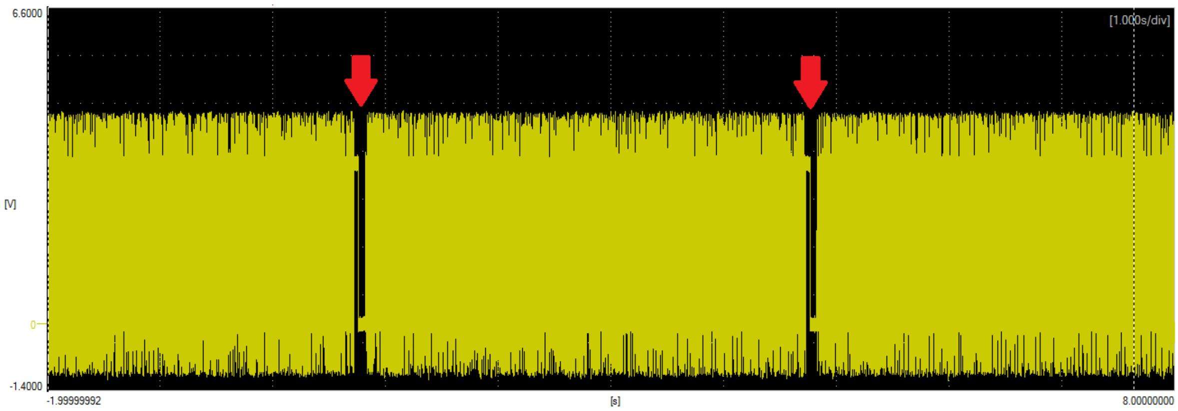


Figure 4-15: 100 Millisecond transmission break after at most 4 seconds of radiation

4-4-4 Conclusion

Athletes are missed due to the protocol setup, due to bad antenna reception and due to government regulations. There is a tradeoff between number of hits (accuracy) and missed athletes. A higher density causes more misses and a lower number of hits. Issues with the government regulations could be solved with frequency hopping. The goal of the reader protocol should be to detect all athletes with as much hits as possible.

4-5 Multiple antennas

The BibTag system has multiple antennas. A timing line consists of mats and each mat has a reading antenna. If multiple antennas try to communicate at the same time with a common tag population, then issues may occur. The BibTag system solves this by switching between the four antennas. If more than four mats are installed, then multiple readers are necessary. Switching between multiple antennas and multiple readers in the environment may affect the accuracy and detection rate.

4-5-1 Antenna switching

If an athlete runs over a mat, then it will be seen by this antenna a quarter of the time. The rest of the time the reader makes use of the other three antennas. It may be seen by other antennas, but this will be with lower signal strength. The BibTag system just picks the detection (hit) with the strongest signal. Because the strongest signal can only be detected a quarter of the time, the accuracy is affected by antenna switching. However, if an antenna sees less BibTags in the field or no BibTags at all, then it will switch faster to the next antenna. An antenna with a reduced radiating signal results in faster switching. Currently the reader reads the athletes twice in a row. An optimized reader may improve the switching speed by reader athletes only once a time. Faster switching led to more (spread) hits in the same time, a lower risk of missing an athlete and a better hit/strength pattern. Furthermore it is better for the detection rate to not switch the antennas in the pattern 1 -> 2 -> 3 -> 4 -> 1, but to switch 1 -> 3 -> 2 -> 4 -> 1. Since athletes are visible for 2 or 3 antennas, a weaker BibTag should then be detected earlier.

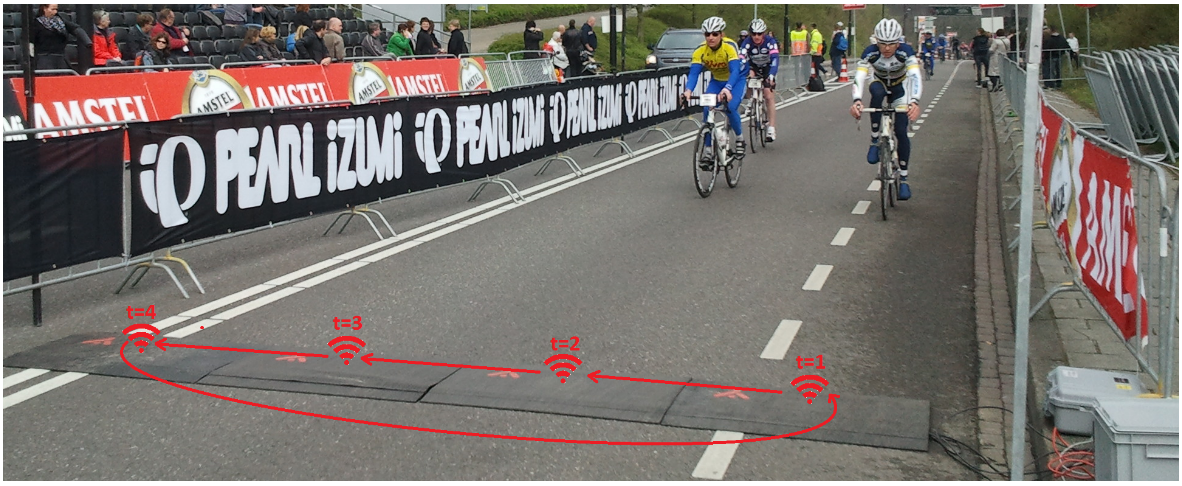


Figure 4-16: Antenna switching (source: MYLAPS)

4-5-2 Pattern recognition

Part is removed (Confidential)

4-5-3 Conclusion

Antenna switching may cause inaccurate time results and detection misses. A faster and different switching pattern would lead to a better accuracy and less detection misses. Furthermore could the accuracy of the time results be improved if pattern recognition is applied.

4-6 Summary

The BibTag sports timing system is dealing with four major challenges: *throughput, accuracy, missing detections and multiple antennas*. Throughput is the number of athletes that can cross a start or finish line within a time period. A maximum of 52 athletes is found at the start of the Valencia Marathon 2011. If the throughput is too high then this leads to missing athletes. Not missing detections is one of the most critical requirements for sport timing. If the time of an athlete is not recorded then the final results are not correct. A tradeoff has to be made between the accuracy of the time results and the number of missed detections. To obtain an accurate passing time an athlete should be detected multiple times (hits). However, more hits can result in more missing detections. A higher throughput both affect the accuracy and the number of missed detections in a bad way. The goal for mass events is to have no missing detections and obtain as much accurate times as possible. Timing lines have multiple antennas. These antennas cannot communicate at the same time and therefor they switch in time. Switching antennas can affect the accuracy, the throughput and the number of missed detections. A more optimized switching pattern would lead to less missing detection and more accurate times. For a complete table summary of the challenges and the corresponding solutions see Table 4-3.

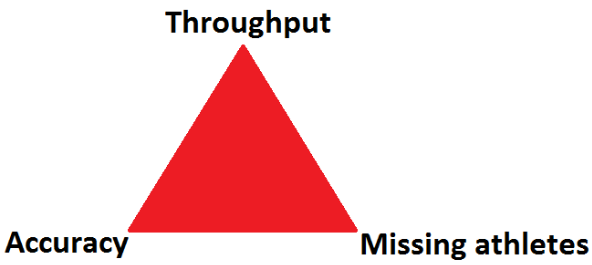


Figure 4-17: Accuracy vs missing athletes vs throughput

Throughput
Summary: Starts can be very busy and the number of athletes who cross the start line within a period can be very high. This can lead to not recorded athletes and inaccurate registered times. *Solution:* - Faster antenna switching with fewer athletes to read by the antenna leads to less risk of missing an athlete and the throughput can be higher. - More efficient reading process
Accuracy
Summary: For correct results athletes should be distinguished if they finish a short period apart. To be able to discriminate between athletes the system has to be accurate enough. Athletes should be read multiple times to obtain an accurate time. However, more reads per athlete causes a higher risk of missing an athlete. *Solution:* - Obtain more hits per athlete. This is obtained with a more efficient reading process and a faster and better antenna switching pattern
Missing athletes
Summary: One of the most critical requirements of a timing system is that the athlete should always be detected. However a high throughput in combination with the reader protocol can lead to missed athletes. *Solution:* - Faster antenna switching with fewer athletes to read by the antenna leads to less risk of missing an athlete. BibTags with bad reception are then easier to read. - More efficient reading process
Multiple antennas
Summary: A timing line has multiple antennas. The antennas cannot communicate at the same time and therefore antenna switching is applied. Slow switching causes inaccurate registered times and a higher risk of missed athletes. Slow switching is caused by high throughput and the reader protocol. *Solution:* - Athletes are read two times short after each other. For sports timing it is better to do it ones and switch faster. - Reduced antenna signal results in less athletes and shorter rounds. - A different switching pattern is applied. Instead of 1->2->3->4->1 will be applied 1->3->2->4->1.

Table 4-3: Summary of the challenges and pointable solutions

Chapter 5

MYLAPS UHF Reader

5-1 Problem definition

As of today UHF Sport timing systems make use of standard UHF RFID readers. The standard readers are commonly used in other industries, e.g. in warehouses to keep the stock up to date by tracking goods leaving and arriving the warehouse. The sports timing company would like to build their own for sports timing optimized UHF RFID reader. In the previous chapter are five major challenges for sports timing described: throughput, accuracy, missing detections, antenna switching and government regulations. The reader should be optimized to deal with these challenges.

This thesis focusses on the communication protocol between the BibTags (tags worn by the athletes) and the reader. However, the BibTags are standard low-cost RFID tags and cannot be optimized. Only an adaption of the reader could lead to an optimization. The reader should apply to the RFID Class 1 Gen 2 protocol to be able to communicate with the BibTags. The Class 1 Gen 2 protocol describes how a tag replies on commands send by the reader. The reader is free to determine which commands are sent at what time. The reader takes the lead and tells which athletes may send their identification number at what time. The optimization consists of this part. An optimized reader algorithm for sports timing improves the throughput and accuracy.

In this chapter several reader algorithms are proposed, analyzed and simulated for sports timing. Furthermore is the currently used standard UHF RFID reader discussed in a detailed matter. At last but not least is proposed an optimized reader algorithm for sports timing.

Characteristics of a sports timing reader

The sport timing specific challenges lead to the following main goals for the reader algorithm:

1. Read all unique tags and do not miss an athlete.
2. If all unique tags are read, then read each tag as much as possible.

The reader algorithm has to deal with the unique characteristics of sports timing:

- Small tag populations. Less than 50 tags are common. A $Q > 7$ will not appear.
- Athletes are in the field for a (short) period of time
- Athletes will enter and leave the field.
- Number of athletes in the field changes over time. However, the difference is slow compared to the operating speed of the reader.
- Athletes are moving
- Antenna strength varies over time and athletes may have bad reception.

5-2 Comparison of reader algorithms

The performance of RFID Gen 2 anti-collision protocol depends on the transmission scheme that controls access to the shared medium. The EPC Global Class 1 Gen 2 protocol is based on slotted ALOHA. Channel access is obtained on a Time-Division Multiple Access (TDMA) basis. Tags that want to communicate take access of the shared medium in random timeslots. The performance is highly influenced by the number of tags in the field and the number of timeslots. If multiple tags take access of the shared medium, then a collision occurs and transmission may be corrupt. Since tags take access on random timeslots, slotted ALOHA is a probabilistic algorithm. If the number of timeslots is way more than the number of tags, then the probability of collisions is low. However, the number of slots where nobody makes use of the medium is high. To obtain a high efficiency the optimal mix of timeslots with a given number of athletes in the field should be taken. Nevertheless, the number athletes is not given and it changes over time. For that reason an approximation has to be made. Eight algorithms are analyzed for sports timing. These algorithms are different in the way they estimate the number of athletes in the field and how they determine the number of timeslots.

All algorithms obtain the best performance if the number of timeslots is optimal for the number of athletes in the field. This optimum is found when there are as much single tag replies as possible. Or in other words, the number of empty slots and collisions should be reduced to a minimum. The following proof shows that *an optimum efficiency is found when number of timeslots is equal to the number of athletes.*

The probability that k of the n athletes respond in a slot given a frame size of 2^Q is binomially distributed

$$P_k = \binom{n}{k}\left(\frac{1}{2^Q}\right)^k\left(1 - \frac{1}{2^Q}\right)^{n-k} \tag{5-1}$$

The probability of a single tag reply P_{Read}, an empty slot P_{Empty} and the probability that a collision occurs in a slot $P_{Collision}$ are then given by

$$P_{Read} = \binom{n}{2^Q}\left(1 - \frac{1}{2^Q}\right)^{n-1} \tag{5-2}$$

$$P_{Empty} = \left(1 - \frac{1}{2^Q}\right)^{n} \tag{5-3}$$

$$\begin{aligned} P_{Collision} &= \sum_{k=2}^{n} \binom{n}{k}\left(\frac{1}{2^Q}\right)^{k}\left(1 - \frac{1}{2^Q}\right)^{n-k} \\ &= 1 - P_{Read} - P_{Empty} \\ &= 1 - \left(1 - \frac{1}{2^Q}\right)^{n}\left(1 + \frac{n}{2^Q - 1}\right) \end{aligned} \tag{5-4}$$

The optimal Q is found, when the derivative of P_{Read} is solved for zero. The number of athletes n is given.

$$\frac{d}{dp}P_{Read} = -\frac{n}{2^Q}(n-1)(1-\frac{1}{2^Q})^{n-2} + n(1-\frac{1}{2^Q})^{n-1} = 0 \tag{5-5}$$

$$\begin{aligned} \frac{n}{2^Q}(n-1)(1-\frac{1}{2^Q})^{n-2} &= n(1-\frac{1}{2^Q})^{n-1} \\ \frac{1}{2^Q}(n-1) &= 1 - \frac{1}{2^Q} \\ \frac{1}{2^Q}(n-1) &= \frac{1}{2^Q}(2Q-1) \\ n &= 2^Q \\ Q_{optimal} &= log_2(n) \quad \text{iff n is a power of 2} \end{aligned} \tag{5-6}$$

The optimal probability is then $P_{Read\_optimal}$ for $2^Q = n$ athletes

$$P_{Read\_optimal} = \left(1 - \frac{1}{n}\right)^{n-1} \tag{5-7}$$

For a large number of athletes P_{Read} converge to 36,8%:

$$\begin{aligned} \lim_{n\to\infty} P_{Read} &= \lim_{n\to\infty}\left(1 - \frac{1}{n}\right)^{n-1} \\ &= \frac{1}{e} \\ &\approx 36,8\% \end{aligned} \tag{5-8}$$

Figure 5-1 shows a plot for the probability of a successful read when n athletes are in the field and a frame size of 2^Q is used. For best efficiency an optimal Q should be chosen. Table 5-1 shows what Q to be chosen when n athletes are expected in the field, even when n is not a power of 2.

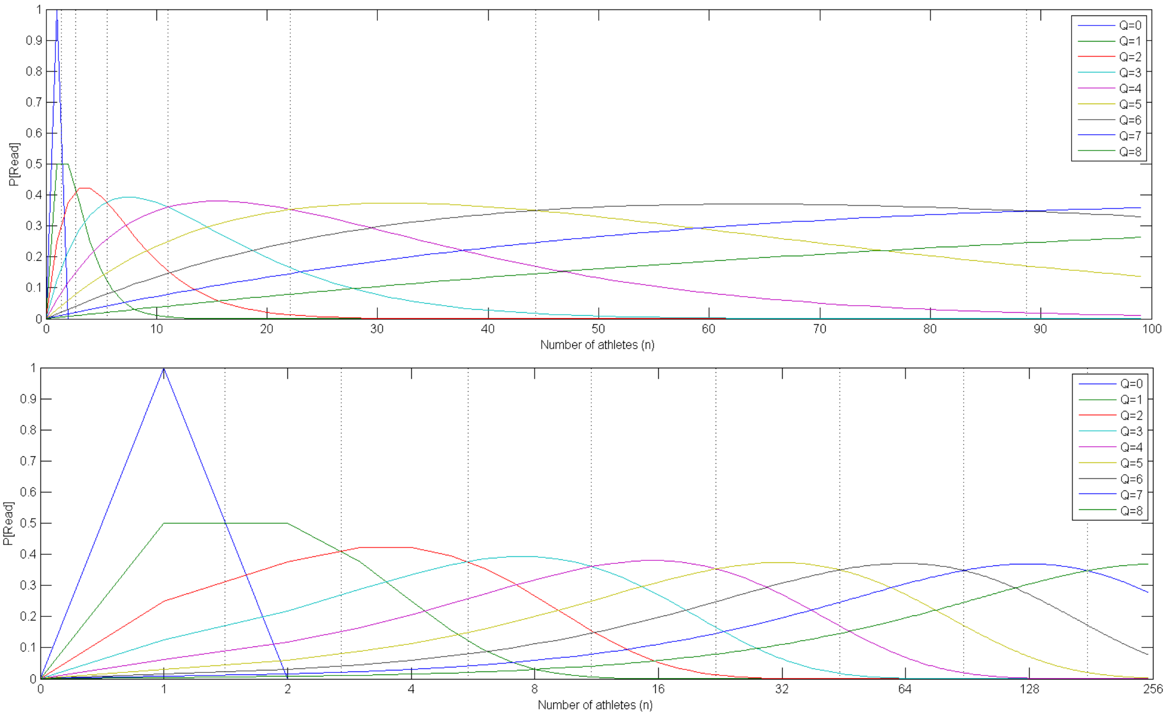


Figure 5-1: Optimum efficiency is found when 2^Q is equal to number of athletes

Athletes	Optimal Q
0-1	0
2	1
3-5	2
6-11	3
12-22	4
23-44	5
45-88	6
89-177	7
178-354	8

Table 5-1: Optimal number of slots for an expected number of athletes

5-2-1 Basic Frame Slotted ALOHA

Basic Frame Slotted ALOHA (BFSA) is characterized by cycles (frames) with a *fixed number of timeslots*. Each cycle all tags are invited. Since the size of a cycle is fixed, the implementation of the algorithm is simple. However, efficiency drops drastically when the number of athletes is more than the number of timeslots. In that case slots are filled with collisions and tags cannot be read. On the other side time is wasted when the number of timeslots is way more than the number of athletes in the field. The shared channel is in that case not used for a long time. Since every cycle new and already read athletes participate it is possible that athletes collide every cycle till they leave the field and have no recorded time.

The probability of missing a tag after C cycles can be given by

$$\begin{aligned} P_{missing\_athlete} &= \prod_{c=1}^{C}\left(1-\frac{2^Q}{n_c}P_{Read}\right) \\ &= \prod_{c=1}^{C}\left(1-\left(1-\frac{1}{2^Q}\right)^{n_c-1}\right) \end{aligned} \tag{5-9}$$

The expected number of hits after C cycles is given by

$$\begin{aligned} E[Hits] &= \sum_{c=1}^{C}\left(\frac{2^Q}{n_c}P_{Read}\right) \\ &= \sum_{c=1}^{C}\left(\left(1-\frac{1}{2^Q}\right)^{n_c-1}\right) \end{aligned} \tag{5-10}$$

In Figure 5-2 and Figure 5-3 are given a plot for the probability of missing an athlete and the expected number of hits when a frame size of 2^Q is used and number of athletes in the field is N. The plot assumes that standard reader settings are used. Athletes can be seen by the antenna in a range of 10 meters. The running speed is 5 m/s and the athlete is visible by the antenna for 2 seconds. Timing settings of a European reader with Miller 4 encoding are used. Since the motion of the athletes is way slower than the speed of the reader, expected is that the number of athletes that leave the field is equal to number of athletes that enter the field.

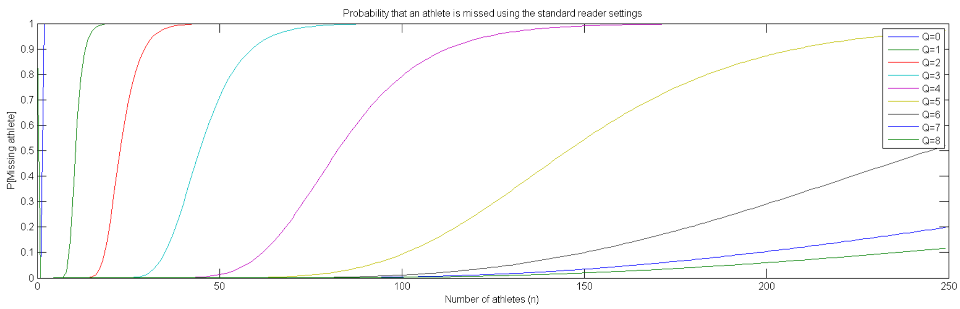


Figure 5-2: Probability of missing an athlete using BFSA and standard reader settings

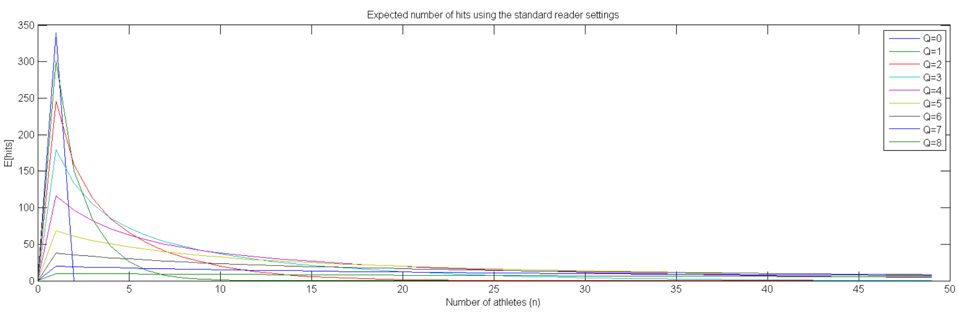


Figure 5-3: Expected number of hits using BFSA and standard reader settings

Basic Frame Slotted ALOHA may work well for situations where the number of tags in the field does not change over time. However, with sports timing the number of athletes change over time. The number of hits will be very low in quiet situations and tags may be missed in busy situations. An enhancement for sports timing is an algorithm where the frame size does change dynamically over time. In the next section are algorithms proposed that adapt the frame size dynamically. These algorithms are called Dynamic Frame Slotted ALOHA.

5-2-2 Dynamic Frame Slotted ALOHA

One of the characteristics of sports timing is that the number of athletes that cross a timing line changes over time. For example a start of a marathon is busy and a finish is relatively quiet. But even a quiet finish can be busy for some period when a big group crosses the finish line. To obtain an efficient system with a high number of hits adjustments has to be made during the reading process. Dynamic Frame Slotted ALOHA (DFSA) *adapts the frame size every cycle*. The reader changes the frame size to a size that is optimized for the expected number of athletes in the next cycle. The determination of the number of athletes in the next cycle is an estimation made based on the number of collisions, reads or empty slots. The estimate can be done at the end of the cycle (frame-by-frame), but can also be done during a cycle (slot-by-slot). The reader is then able to take action during a cycle by ending the cycle and starting a new one with a better frame size. Eight algorithms are analyzed. These algorithms have a different approach for estimating the number of athletes in the field and changing the size of a cycle to the expected optimal frame size. The algorithms are compared for their usage in sports timing. A summary of all algorithms is given in table Table 5-3.

Slot-count (Q) selection algorithm The slot-count selection algorithm is the standard algorithm proposed by the EPC Global RFID Class 1 Gen 2 protocol [3]. It is a slot-by-slot based estimator and is different in a way that it does not make use of frames. Figure 5-4 illustrates the principle of the algorithm. The algorithm stops the frame after only one slot and starts immediately a new round. Depending on the answer it gets in that slot the reader makes a new estimate for the number of athletes in the field and adapts the Q if necessary. The value of Q in that round determines the probability that a successful read takes place in the slot and an optimum Q should increase the performance.

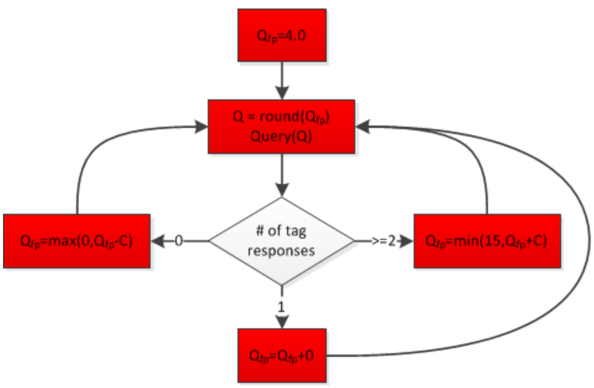


Figure 5-4: Slot-count selection algorithm

The basis of the estimation is a floating point presentation of Q. According to the number of responses in the slot the floating point presentation of Q is incremented or decremented with a constant C. When no replies occur in a slot it could mean that the frame size is too big and the Q_{fp} will be decremented. When two or more replies take place it is a sign that the frame size is too small and Q_{fp} will be incremented. The rounded value of Q_{fp} is used in the next slot and is communicated to the tags with a Query command. The constant C determines the speed and accuracy of convergence to the optimal Q. Typically a smaller value of C is chosen for low values of Q and a bigger value of C is chosen for high values of Q. Research is done in [11] to find the optimum C value for each Q. These results are given in Table 5-2. In [12] a normalized value of C is proposed. Empirical results in that paper shows that $C = 0.8/Q$ perform best.

Q	Frame size	C	Q	Frame size	C
1	2	0.5	9	512	0.2
2	4	0.5	10	1024	0.2
3	8	0.5	11	2048	0.1
4	16	0.5	12	4096	0.1
5	32	0.5	13	8192	0.1
6	64	0.5	14	16384	0.1
7	128	0.4	15	32768	0.1
8	256	0.3			

Table 5-2: Optimum value of C for each frame size

Advantage of the slot-count selection algorithm is that it converges to the optimum Q value very quickly. It evaluates the frame size on a slot-by-slot basis instead of a frame-by-frame basis as some other schemes do. However, starting a new round after each slot takes a lot of time. The Query command needs 22 bits, where a simple QueryRep command only takes 4 bits [3]. A QueryRep command is normally used to pronounce a new slot in a fast way within a frame and this algorithm does not make use of this advantage. The algorithm also does not take account of multiple antennas and dual targets. The algorithm works good for systems having one antenna and tags that needs to be read only once. Nevertheless, sport timing systems have multiple antennas and tags needs to be read multiple times to obtain accuracy. The proposed solution in this thesis is to have a floating point presentation of Q for each antenna. The self-adapting mechanism of Q is then able to operate for each population.

Q^+ algorithm The Q^+ algorithm is proposed by the authors in [13] as an improvement on the standard slot-count selection algorithm. The efficiency is increased by modifying and optimizing the parameters of the slot-count selection algorithm. The authors suggest that two identical C values for both the collision cases and idle cases is not the ideal solution. This is because the probability of a collision in a slot is not equal to the probability of no responding tags. The parameter C is in this paper split into two different parameters, C_i and C_c. The ratio of these parameters is as follows:

$$\frac{C_c}{C_i} = \frac{P_{Collision}}{P_{Empty}} = \frac{1 - \left(1 - \frac{1}{2^Q}\right)^n \left(1 + \frac{n}{2^Q - 1}\right)}{\left(1 - \frac{1}{2^Q}\right)^n} \tag{5-11}$$

For an optimum Q and for higher values of n, this equation converges to:

$$\lim_{n\to\infty} \frac{1-\left(1-\frac{1}{n}\right)^n\left(1+\frac{n}{n-1}\right)}{\left(1-\frac{1}{n}\right)^n} = e-2 \tag{5-12}$$

Conclusion of these authors is that the ratio of $\frac{C_c}{C_i}$ is a more critical factor than the scale. The value of C_c can therefore be set arbitrary between 0.1 and 0.5 if the number of tags in the field is unknown. Nevertheless, simulation results show that if the number of tags is known or can be estimated, the corresponding C_c and C_i are:

$$\begin{aligned} C_c &= -0.0491 \ln n + 0.534 \\ C_i &= (e-2)C_c \end{aligned} \tag{5-13}$$

In consideration must be taken that this ratio only holds for a large number of tags. One of the characteristics of sports timing is that the number of tags in the field is low.

In [14] the authors have the same conclusion that the C constant should be split in two values. The two control parameters are this time not a ratio, but are calculated based on the reader-to-tag and tag-to-reader data rates. The basic idea is that the average time of a collision takes more time than the average time of an empty slot. An empty slot is more preferred than a slot with a collision. The enhancement in this algorithm is that both C parameters are based on the average collision and idle times and are not identical like in the original algorithm. The following C_c and C_i are suggested:

$$\begin{aligned} C_c &= 0.1 \\ C_i &= min\left(0.1, \frac{T_{coll\_avg}}{T_{idle\_avg}} C_c\right) \end{aligned} \tag{5-14}$$

Besides the division of the C constant, the authors also suggest to make use of the QueryRep command. The original EPC Global algorithm does not make use of the QueryRep command, but only makes use of the Query command. The Query command is 22 bits, where the QueryRep command is only 4 bits. Since a Query command is only necessary to pronounce a new Q value, suggested is to use the QueryRep command if the rounded value of Q_{fp} is not changed and use the Query command if it is changed. The algorithm is schematically shown in Figure 5-5.

Schoute's Backlog Estimation Algorithm The algorithm proposed by Schoute [6] estimates the number of tags in the field by means of some heuristic. When the expected number of athletes in the field is computed, then the corresponding optimal frame size can be set for best throughput. The estimation is made based on the number of garbled slots (collisions) and successful reads observed in the previous frame.

In [6] is assumed that the number of tags transmitting in a time slot is Poisson distributed. In optimal condition the mean of the Poisson distribution is 1. This is the case when the number of tags in the field is equal to the number of slots in the frame. However, the Poisson

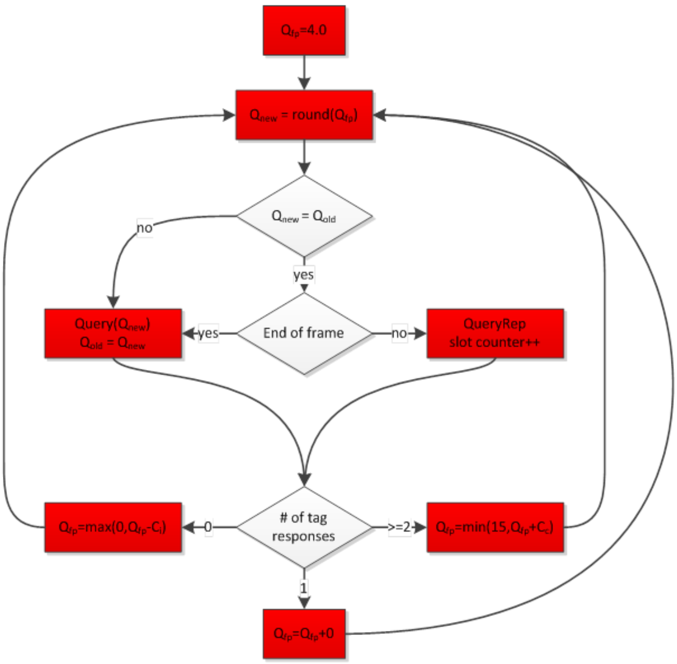


Figure 5-5: Q^+ algorithm

distribution is only valid for larger numbers of athletes (>10). The probability that k tags choose a certain time slot is then:

$$Pr[k \text{ tags reply in slot } i] = P_k = e^{-1}\frac{1}{k!} \tag{5-15}$$

If a time slot is observed garbled, then the number of responding tags is at least 2. Given that a time slot is garbled, the (posteriori) distribution can be calculated using Bayes' theorem:

$$Pr[k \text{ tags reply in slot } i \mid \text{garbled}] = P_{k|garbled} = \begin{cases} 0 & \text{if } k = 0 \text{ or } 1 \\ \frac{P_k}{1-P_{Empty}-P_{Read}} & \text{if } k \geq 2 \end{cases} \tag{5-16}$$

The expected number of tags that replied in the garbled slot, assuming that frame size was chosen optimal, is:

$$E[k|\text{garbled}] = \sum_{k=2}^{\infty} kP_{k|garbled} = \frac{\sum_{k=2}^{\infty} e^{-1}\frac{1}{(k-1)!}}{1-2e^{-1}} = \frac{e-1}{e-2} \approx 2.39 \tag{5-17}$$

In the knowledge that the expected value is 1 for a successful read and is 0 for an empty slot, the estimated number of tags in the last frame is:

$$n = 2.39 \cdot N_{Coll} + N_{Reads} \tag{5-18}$$

The estimated backlog, the tags that still needs to be read in the next frame is then:

$$N_{Backlog} = 2.39 \cdot N_{Coll} \tag{5-19}$$

Where N_{coll} is the number of collision slots in the last frame.

Unique in this algorithm is that it calculates the backlog, the number of tags that still needs to be read. The proposed algorithm works for that reason with ALOHA periods. An ALOHA period (or inventory round) consists of multiple frames necessary to read the tags that are invited at the beginning of the period. New tags will not be invited and have to wait till the period is finished. Since no new tags participate in the next frame, the expected number of tags in the backlog should also be the size of the next frame. The algorithm converges to a backlog of zero tags, where no garbled slots are found and a new ALOHA period can start. The algorithm proposed by the authors in pseudo code is:

for *each ALOHA period* **do**
  initial parameters:
    λ — new packets/unit of time
    T — time since start of previous period
    $i = 1$ — frame counter
    $n_i = round^{+}(\lambda T)$ — time slots in first frame
  repeat
      observe g_i — garbled slots in frame i
      $n_{i+1} = 2.39 \cdot g_i$ — time slots in next frame (rounded)
      $i = i + 1$ — increment frame counter
  until $n_i = 0$;
end

Algorithm 1: Schoute's Backlog Estimation

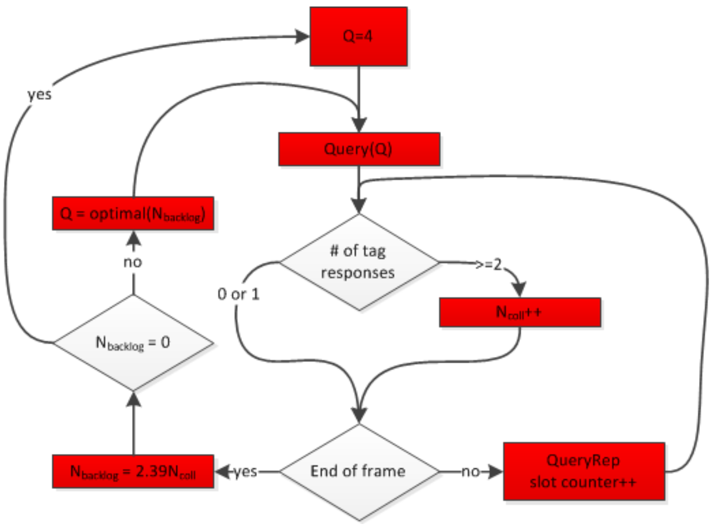


Figure 5-6: Schoute algorithm

The effects of noise and capturing are not taken into account in this algorithm. Noise implies the probability of a garbled slot, when only one tag or no tags reply in a slot. Capturing means the probability of a successful read when two or more tags reply in a slot. This could be the case when for example one tag is closer to the antenna and overpowers the other tag. The authors in [15] presents a correction for noise and capturing:

$$N_{Backlog} = H \cdot N_{Backlog\_est}$$
$$\begin{cases} H = 1 - 1.4 & \text{passive tag} \\ H = 0.8 - 1 & \text{active tag} \end{cases} \tag{5-20}$$

Authors in [6] assume that frames could have all integer values. However, frames lengths are limited by the power-of-two constraint. The Poisson distribution with a mean of 1 is in that case not valid, due to the expectation that the number of slot is equal to the number tags. This leads to deviations between the estimated number of tags and the true number of tags present.

The effect of ALOHA periods can be positive for Sports Timing. Athletes with bad antenna reception, for example misplaced tags, are then able to respond and will not be overpowered by athletes with better antenna reception. In theory all athletes will be read, if and only if the athletes stay long enough in the field. Using single frames athletes could collide every frame if they have bad luck. Already read athletes will not compete in the next frame with athletes that still need to be read. However, ALOHA periods take longer than a single frame. An athlete that is visible for an antenna just for a short period of time can then be missed. Expected is that the number of hits will be lower on average.

Cha's C-ratio Tag Estimation Method The algorithm proposed by [16] is a frame-by-frame based algorithm. The amount of garbled slots at the end of a frame gives an indication for the number of athletes in the field. An estimation is made based on the ratio of garbled slots in a frame by the following formula:

$$C_{ratio} = \frac{N_{Coll}}{2^Q} = 1 - \left(1 - \frac{1}{2^Q}\right)^n \left(1 + \frac{n}{2^Q - 1}\right) \tag{5-21}$$

The C-ratio is exactly the same as the probability of a garbled slot, given in equation (5-4). Since the Q is specified by the reader at the beginning of a frame and the number of garbled slots can be calculated at the end of a frame, the number of athletes in the field n can be derived from equation (5-21). The algorithm assumes independent binomial distribution of the tags in each slot.

Chen's Tag Estimation Method The previous algorithms in [6] and [16] have only a single parameter (number of collisions) to perform the estimation. The estimation method proposed in [17] makes use of two parameters: the number of empty slots and the number of successful reads. The expected number of reads and collisions in a frame can be calculated using (5-2) and (5-3).

$$E[Read] = 2^Q \cdot P_{Read} = n\left(1 - \frac{1}{2^Q}\right)^{n-1} \tag{5-22}$$

$$E[Empty] = 2^Q \cdot P_{Empty} = \left(1 - \frac{1}{2^Q}\right)^n \tag{5-23}$$

Solving equation (5-22) and (5-23) for n gives the expected number of athletes in the field.

$$n = (2^Q - 1)\frac{E[Read]}{E[Empty]} = (2^Q - 1)\frac{N_{Read}}{N_{Empty}} \tag{5-24}$$

However, if $N_{Reads} = 0$ or $N_{Empty} = 0$ then n is undefined or returns zero. The authors suggest to use in these cases an upper bound or a lower bound:

$$\begin{array}{lll} 1) & N_{Read} = 0, N_{Empty} = 0 & \text{Upper bound} \\ 2) & N_{Read} \neq 0, N_{Empty} = 0 & \begin{cases} N_{Coll} \geq N_{Read} & \text{Upper bound} \\ N_{Coll} < N_{Read} & \text{Lower bound}(2 \cdot N_{Coll}) \end{cases} \\ 3) & N_{Read} = 0, N_{Empty} \neq 0 & \text{Lower bound}(2 \cdot N_{Coll}) \end{array} \tag{5-25}$$

The use of upper and lower bounds could affect the performance for sports timing. Since one of the characteristics of sports timing is that the number of athletes within the antenna range is low, the probability that there are no reads or no empty slots in a frame is high. Expected is that the effect of the upper bound will result in high time penalties and bad performance.

Vogt's Minimal Error and Lower Bound Method Vogt [18] proposes two methods to estimate the number of athletes in the field at the end of a frame. Both methods are frame-by-frame. The first method performs the estimation using all three parameters: the number of empty, successful and collision slots. The actual values are compared with the binomial expected values, for all values of n. The n with the minimal value of the Euclidean distance (minimal error) is then closest to the number of athletes in the field. The calculation can be performed with the following equation:

$$n = min_n \left| \begin{pmatrix} E[Empty|Q, n] \\ E[Read|Q, n] \\ E[Collision|Q, n] \end{pmatrix} - \begin{pmatrix} N_{Empty} \\ N_{Read} \\ N_{Collision} \end{pmatrix} \right| \tag{5-26}$$

The binomial expected values can be performed with equations (5-27), (5-28) and (5-29).

$$E[Empty|Q, n] = 2^Q \cdot P_{Empty} = 2^Q \left(1 - \frac{1}{2^Q}\right)^n \tag{5-27}$$

$$E[Read|Q, n] = 2^Q \cdot P_{Read} = n \left(1 - \frac{1}{2^Q}\right)^{n-1} \tag{5-28}$$

$$E[Collision|Q, n] = 2^Q - E[Empty] - E[Read] \tag{5-29}$$

The second estimation method proposed is a lower bound estimation for the number of athletes in the field. Given the actual statistics of the number of successful a collision slots at the end of a frame, the lower bound can be calculated with:

$$n_{Lower\_Bound} = N_{Read} + 2 \cdot N_{Collision} \tag{5-30}$$

For every collision are at least two tags required and for a successful read one. The equation is based on this principle. Simulations in [18] shows that the lower bound technique is quite accurate for a small population of tags, but lose accuracy fast when the population becomes bigger.

Chen's Maximum Likelihood Method The optimal frame size estimation method proposed in [19] is a Maximum Likelihood estimator. The actual statistics at the end of a frame (number of empty slots, reads and collision slots) provides the parameters for an underlying model.

This model produces a probability distribution for the number of athletes. The maximum value of the distribution will be likely the number of athletes in the field. The underlying model is based on the well-known occupancy problem [20]. The occupancy problem describes the probability of finding exactly k slots occupied with m athletes (tags):

$$P(k,m|n) = \frac{(-1)^m 2^Q! n!}{m! 2^{Qn}} \sum_{j=m}^{min(2^Q,\lfloor \frac{n}{k} \rfloor)} (-1)^j \frac{(2^Q-j)^{n-jk}}{(j-m)!(2^Q-j)!(n-jk)!(k!)^j} \tag{5-31}$$

The probability distributions for empty slots and successful slots are then:

$$P(0,N_{Empty}|n) = \frac{(-1)^{N_{Empty}} 2^Q!}{N_{Empty}! 2^{Qn}} \sum_{j=N_{Empty}}^{2^Q} (-1)^j \frac{(2^Q-j)^n}{(j-N_{Empty})!(2^Q-j)!} \tag{5-32}$$

$$P(1,N_{Read}|n) = \frac{(-1)^{N_{Read}} 2^Q! n!}{N_{Read}! 2^{Qn}} \sum_{j=N_{Read}}^{min(2^Q,n)} (-1)^j \frac{(2^Q-j)^{n-j}}{(j-N_{Read})!(2^Q-j)!(n-j)!} \tag{5-33}$$

The n with the maximum probability is then likely the number of athletes in the field. Taking both the empty slots and reads in consideration the combined formula is given by:

$$P(N_{Empty},N_{Read}|n) = P(0,N_{Empty}|n) \cdot P(1,N_{Read}|n) \tag{5-34}$$

Knerr's Slot-by-slot Maximum Likelihood Estimation The algorithm proposed by Knerr [21] is a multi-parameter estimation. Both the number of empty slots and the number of reads are taken into account to obtain a more reliable estimation. The algorithm is based on a binomial distribution and a new estimation is composed each slot. Therefor it is possible to take action during a frame, when for example the frame is way too small or way too big. The formula is derived from the distribution function published in [18]. It returns the probability that n tags are in the field when N_{Read} and N_{Emply} slots are observed. The n with the maximum probability is then likely the number of athletes that are in the field during the frame. The derived formula from [18] for a single parameter is:

$$P[X_r = m_r|N,n] = \binom{N}{m_r} \left[\prod_{l=0}^{m_r-1} \binom{n-lr}{r} \left(\frac{1}{N}\right)^r \right] \sum_{k=0}^{min(N-m_r,\lfloor \frac{n-rm_r}{r} \rfloor)} (-1)^k \binom{N-m_r}{k} \left[\prod_{j=0}^{k-1} \binom{n-rm_r-jr}{r} \left(\frac{1}{N}\right)^r \right] \left(\frac{N-m_r-k}{N}\right)^{n-m_r r-kr} \tag{5-35}$$

The basic idea behind the formula is a set of matrices with all possible outcomes. Each matrix has N columns (one for each slot) and n rows (one for each tag). The value of each element is 1 if the tag responds in that slot and zero if not. There are N^n of such matrices. Relevant are the matrices where exactly m_r columns have r tags. The number of matrices satisfying the condition divided by the total number of matrices returns then the probability of the condition.

For the condition that exactly N_{Empty} slots have zero tags in it and all other slot have at least one tag, given that S slots of the N are passed is:

$$P[X_0 = N_{Empty}|S,N,n] = \binom{S}{N_{Empty}} \sum_{k=0}^{min(S-N_{Empty},n)} (-1)^k \binom{S-N_{Empty}}{k} \left(\frac{N-N_{Empty}-k}{N}\right)^n \tag{5-36}$$

And for the condition that exactly N_{Read} slots have one tag respond is given by:

$$P[X_1 = N_{Read}|S,N,n] = \binom{S}{N_{Read}} \left[\frac{n!}{(n-N_{Read})!}\left(\frac{1}{N}\right)^{N_{Read}}\right] \sum_{k=0}^{min(S-N_{Read},n-N_{Read})} (-1)^k \binom{S-N_{Read}}{k} \left[\frac{(n-N_{Read})!}{(n-N_{Read}-k)!}\left(\frac{1}{N}\right)^k\right]\left(\frac{N-N_{Read}-k}{N}\right)^{n-N_{Read}-k} \tag{5-37}$$

The combined formula [21] for an estimation of n athletes when N_{Read} and N_{Empty} slots are observed after S of the N slots is then:

$$P[X_r = N_{Empty}, N_{Read}|S,N,n] = \binom{S}{N_{Empty}} \sum_{i=0}^{min\left(\substack{S-N_{Empty}-N_{Read},\\ n-N_{Read}}\right)} (-1)^i \binom{S-N_{Empty}}{i} \left(\frac{N-N_{Empty}-N_{Read}-i}{N}\right)^{n-N_{Read}} \binom{S-N_{Empty}-i}{N_{Read}} \left[\frac{n!}{(n-N_{Read})!}\left(\frac{1}{N}\right)^{N_{Read}}\right] \left[\sum_{k=0}^{min\left(\substack{S-N_{Empty}-N_{Read}-i,\\ n-N_{Read}}\right)} (-1)^k \binom{S-N_{Empty}-N_{Read}-i}{k} \left[\frac{(n-N_{Read})!}{(n-N_{Read}-k)!}\left(\frac{1}{N-N_{Empty}-N_{Read}-i}\right)^k\right]\left(\frac{N-N_{Empty}-N_{Read}-i-k}{N-N_{Empty}-N_{Read}-i}\right)^{n-N_{Read}-k}\right] \tag{5-38}$$

The formula is slot-by-slot and takes both the empty slots and the reads into account. However, the computation is really complex. For larger number of n the factorial of n results in extremely high values.

5-2-3 Simulation results

The performance of each algorithm for the purpose of Sports Timing is obtained with a simulator. The simulator is explained more deeply in Chapter 6. Two races are simulated: Valencia and Boston. For both races a start and a finish. Furthermore are the algorithms simulated with and without taking into account the body influence. The human body affects the antenna signal, causing random noise and bad antenna reception. The performance is split in three parts: accuracy, efficiency and detection.

Accuracy The accuracy of a registered time is indicated by the number of hits. Or in other words: the number of reads per athlete for a single recorded time. The more often an athlete is seen, the more precise is the registration. The average number of hits is equal to the total number of successful readings divided by the total number of athletes. The better an algorithm adapts its frame size to the number of athletes currently in the field, the more hits are obtained. When the number of athletes in the field is low, each athlete can be read more often. This is why the number of hits is way higher at the finish than at the start. Furthermore do inefficient use of commands result in more overhead, a lower reading rate and a lower mean value of hits. The results for the average number of hits per athlete for each simulated algorithm are given in Figure 5-7.

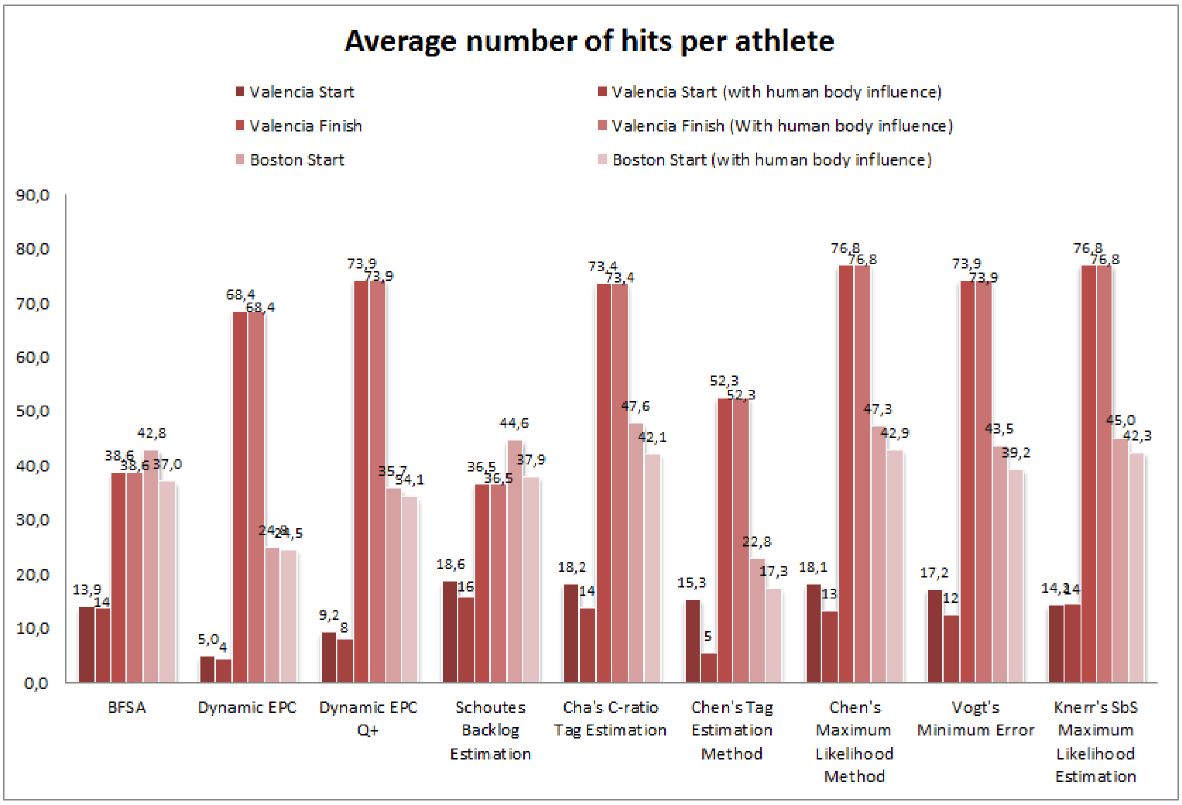


Figure 5-7: Simulation results of the Valencia Marathon

A fixed frame size (BFSA) algorithm shows a quite good performance for a start, but performs really bad for a finish. The algorithm should perform optimal if the number of athletes is always between 12 and 22. However, a finish has most of the time less than 12 athletes in the field and a busy start has more than 22 athletes in the field. Simulations results confirm these expectations and the BFSA algorithm has a low average number of hits during a finish.

The Dynamic EPC and the Dynamic EPC Q+ algorithm adapt the frame slot-by-slot, but have serious long overheads due to the start of a new round each slot. Simulation results show that these overheads drastically influence the number of hits during a start.

Schoutes Backlog Estimation algorithm performs well during a start and bad during a finish. The reason is that the algorithm always starts with a frame of 16 slots. Depending on the number of collisions found during this frame, the next frame will be smaller, bigger or the same size. During a finish the number of athletes is really low. The reader is than busy with the completion of 16 slots instead of reading one or more athletes multiple times. The algorithm works well for higher number of athletes, but performs badly for a low number of athletes in the field. This explains why the simulation shows a low average of hits during a finish but a quite high average during a start.

Chen's tag estimation algorithm has a lower average of hits for both start and finish situations. In spite of taking both the reads and empty slots in consideration, it has a weak spot. The algorithm is based on the ratio between the reads and empty slots. This results in huge time penalties when no reads or no empty slots are found in a frame. For this reason the performance of the protocol is not good for sports timing. In sports timing the number of tags in the field is quite low and it occurs more often that there are no read or no empty slots than for situations where for example thousand tags are in the field. The simulations show the effect of this weak spot and on average less hits are found.

Cha's C-ratio Tag Estimation, Chen's Maximum Likelihood Method, Vogt's Minimum Error and Knerr's SbS Maximum Likelihood Estimation have good results for both the start and finish lines. These algorithms are based on the exact probability computation and are therefore also usable for small amounts of tags. Since one of the characteristics of sports timing is the low density (less than 50 athletes), these algorithms are suitable for sports timing. Cha's C-ratio Tag Estimation only takes the number of collisions in consideration. Chen's Maximum Likelihood Method and Knerr's SbS Maximum Likelihood Estimation are based on two parameters, the reads and the empty slots, and should make a more precise estimation in theory. Vogt's Minimum Error even takes all three parameters into account. The disadvantage of these algorithms is that the exact computation is more complex and especially Knerr's SbS Maximum Likelihood Estimation is hard to compute and cost a lot of time. The Chen's Maximum Likelihood Method is a good combination of complexity and precision and performs best for sports timing.

Efficiency The slot efficiency gives an indication how efficient the radio channel is used. It is the percentage of slots filled with reads out of the total passed slots. A high efficiency corresponds a to good adapting algorithm and an algorithm which has most of the time an optimal frame size. Normally an algorithm with high efficiency has also a high value of hits per athlete. However, the efficiency does not take into account the time wasted due to overhead. The efficiency gives therefore a better indication for the dynamic behavior of the algorithm than the average number of hits. The maximum expected efficiency is given in Figure 5-1. The maximum efficiency can be higher when the number of athletes is low. In example it could be 100% if there is only one athlete and no other athletes at the same time in the field. For higher numbers of athletes the efficiency converges to 36.8%. For that reason finishes have most of the time a better efficiency that starts. The efficiency results obtained with the simulation are given in Figure 5-8.

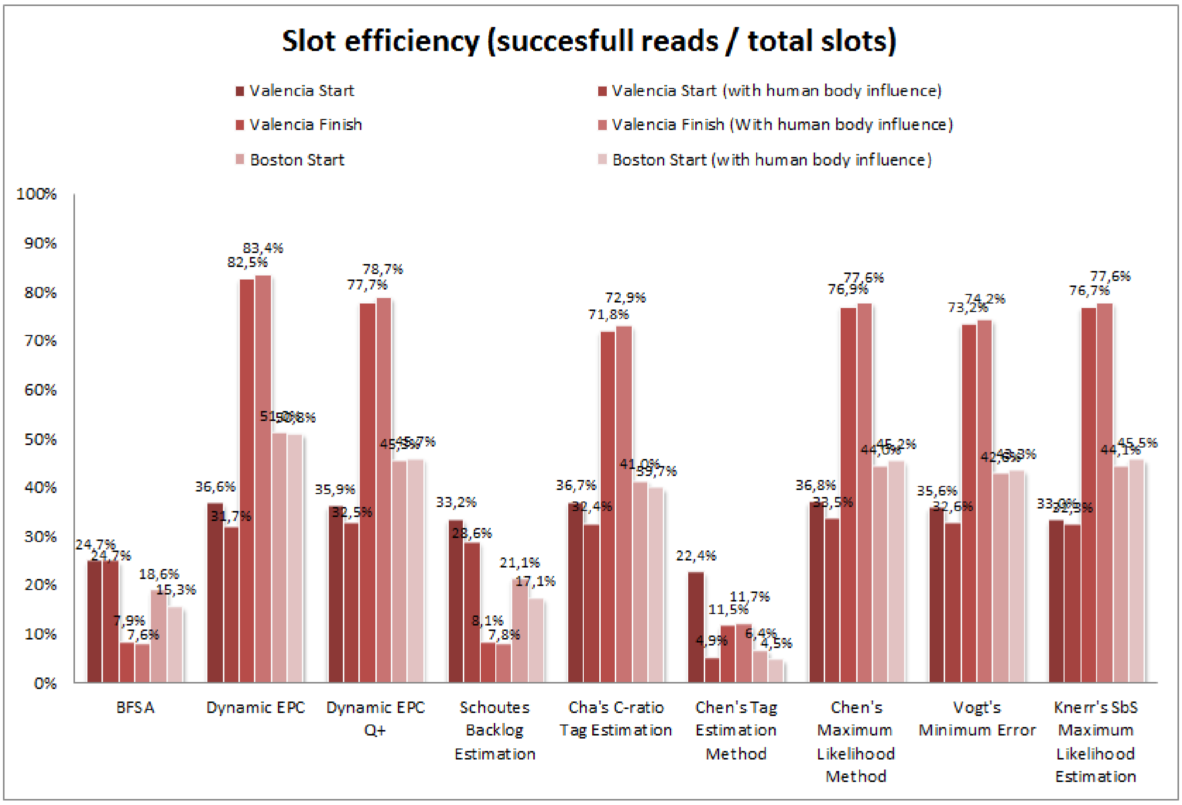


Figure 5-8: Simulation results of the Valencia Marathon

The efficiency results for the Dynamic EPC and Dynamic EPC Q+ algorithms confirm the suggestion that worse average hit performance is caused by the overhead. These algorithms make use of time consuming commands. Both algorithms perform real well for efficiency, but have a low average of hits. Again the Cha's C-ratio Tag Estimation, Chen's Maximum Likelihood Method, Vogt's Minimum Error and Knerr's SbS Maximum Likelihood Estimation have good results for sports timing. Interesting to see is that he slot-by-slot approach of the Knerr's SbS Maximum Likelihood Estimation algorithm does not result in a better efficiency.

Detection performance The detection performance is an indication for the number of athletes that could be missed during a race. The detection performance is the percentage of missed athletes out of the total number of athletes that crossed the timing line. The probability for missing an athlete is higher when a start or finish is busier. The Valencia Start was really busy and has for that reason a low detection performance. In theory the detection performance is no issue for the reader when the density is low. Table 4-2 confirms this statement: when the number of athletes is low, no difference is found between the for throughput optimized backup line and the for more accuracy optimized main line. Furthermore does noise (human body influence) affect the antenna signal and the readability of a tag. In worst case an athlete is missed. For that reason the simulations with the human body influence enabled have also a low detection performance. The detection performance results are given in Figure 5-9.

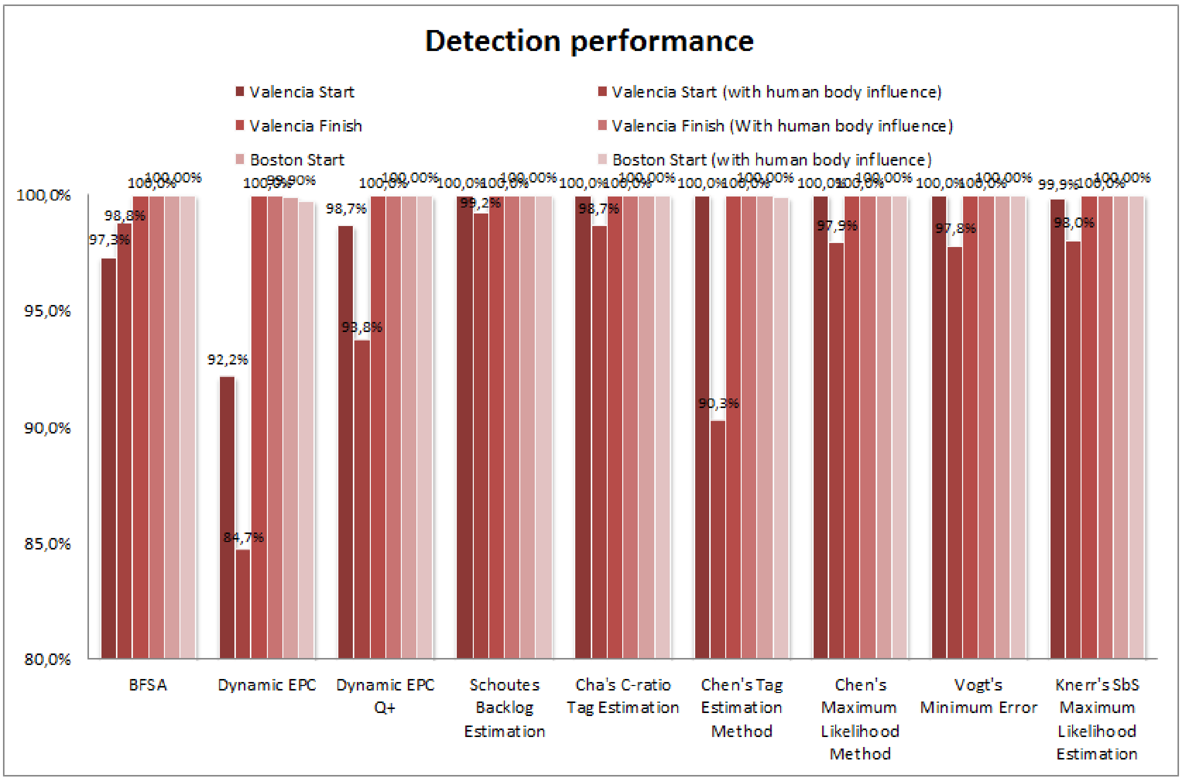


Figure 5-9: Simulation results of the Valencia Marathon

The results for detection performance show the same results found for efficiency and hits performance. Fast adapting algorithms with optimal frame sizes have also a good detection performance. An exception is the Schoutes Backlog Estimation algorithm. It has a good score for detection performance, but has bad performance results for efficiency and average hits. The explanation is that the algorithm makes use ALOHA periods instead of single frames. It reads all tags that are that moment in the field. Already read athletes are then not competing with tags that still need to be read. Since diminishing missing detections is the mail goal for sports timing, ALOHA periods are good for sports timing.

Conclusion The estimation algorithms making use of the exact probability computation perform best for sports timing. Since one of the characteristic of sport timing is that the number of athletes in the antenna range is low (<50), exact probability computation show better results than algorithms based on the assumption that a high number of athletes is within the antenna range ($n \to \infty$). Cha's C-ratio Tag Estimation, Chen's Maximum Likelihood Method, Vogt's Minimum Error and Knerr's SbS Maximum Likelihood Estimation use exact computation and perform well for sports timing. Slot-by-slot algorithms do not show better results than frame-by-frame algorithms. If frame estimation is accurate, then slot-by-slot estimation is unnecessary. The results show that the frame-by-frame algorithms are reliable enough. The use of ALOHA periods instead of single frame result in a better detection performance. In conclusion, for best sports timing performance an optimized algorithm should have an estimation based on the exact probability and should make use of ALOHA periods.

5-2-4 Summary

Slot-count (Q) selection algorithm
Summary: A slot-by-slot based algorithm. A frame is interrupted after only one slot and a new one starts with a new Q. The frame size (Q) is based on a floating point presentation, that increments with a constant C if a collision is occurred in the slot or decrements with C if an empty slot is observed. *Advantages:* - Converges fast to the optimum Q (slot-by-slot) - Simple computation of Q *Disadvantages:* - Lots of overhead due to usage of Query command (22 bits) instead of QueryRep (4 bits) - Has same C for collision and idle slot (less efficient)
Q^+ algorithm
Summary: This algorithm operates the same as the Slot-count selection algorithm, but has some minor changes. Constant C is split in a constant C_c for a collision slot and a constant C_i for an empty slot. Furthermore does it make use of the QueryRep command instead of only the Query command. *Advantages:* - Converges fast to the optimum Q (slot-by-slot) - Has two different C values for a collision and an idle slot (more efficient) *Disadvantages:* - Only optimal for higher number of athletes - Hard to use with multiple antennas and multiple targets - Still a lot of overhead
Schoute's Backlog Estimation Algorithm
Summary: By assuming that the algorithm is Poisson distributed, the expected number of tags that respond in a collision slot can be calculated: 2.39. Based on this number an estimation can be made after a frame when the number of slots with collision and reads are known. Furthermore, no new tags are invited till all tags at the beginning of an inventory round are read. In that case is only the backlog important. *Advantages:* - Simple computation - All tags available at the beginning of an inventory round are read - New tags do not compete with already read tags, due to ALOHA periods - Athletes will always be read if they stay long enough in the field *Disadvantages:* - Only optimal for higher number of athletes - Slower antenna switching (longer inventory rounds) - Makes use of a non optimal start frame size

Cha's C-ratio Tag Estimation Method
Summary: The number of collisions observed in a frame divided by the total number of slots is equal to the probability of a collision in a slot. Using the binomial probability function, the number of athletes can be computed. *Advantages:* - Works for low number of athletes (exact probability computation) - Shows good performance for sports timing *Disadvantages:* - Single parameter could be less accurate - Estimation is unknown if no collisions occur (algorithm is only based on collisions)
Chen's Tag Estimation Method
Summary: The ratio of the expected number of reads to the expected number of empty slots multiplied the frame size minus one results in the exact computation of number of athletes. However, if the number of reads in a frame or the number of empty slots is zero, then the estimation erroneous. *Advantages:* - Works for low number of athletes (exact probability computation) *Disadvantages:* - Is erroneous if the frame does not have empty slots or does not have reads
Vogt's Minimal Error and Lower Bound Method
Summary: The expected values for empty slots, reads and collisions can be calculated for all number athletes (n). The n with the least square error between the real values found in the last frame and the expected values is then probably the the number of athletes is the last frame. *Advantages:* - Works for low number of athletes (exact probability computation) - Takes all three parameters in consideration (empty slots, reads and collisions)
Chen's Maximum Likelihood Method
Summary: The probability of finding exactly m slots with k tags is given by the well-know 'occupancy problem'. With this formulas the probability of finding N_{reads} and N_{empty} are computed. The n with the maximum probability is then likely the number of athletes in the frame. *Advantages:* - Works for low number of athletes (exact probability computation) - Takes two parameters in consideration (empty slots and reads) - Show best results in simulations *Disadvantages:* - Complex computation

Knerr's Slot-by-slot Maximum Likelihood Estimation
Summary: Knerr proposes a slot-by-slot estimation formula that is based on the 'occupancy problem'-formula. The formula calculates the probability that N_{reads}, N_{empty} and $N_{Collisions}$ occur in a frame after S slots. The maximum probability value is then likely the number of athletes in the frame. *Advantages:* - Works for low number of athletes (exact probability computation) - Takes all three parameters in consideration (empty slots, reads and collisions) - Can be used slot-by-slot *Disadvantages:* - Complex computation

Table 5-3: Summary of the anti-collision algorithms

5-3 Standard UHF reader

As of today the BibTag sports timing system make use of a standard UHF RFID Reader. In this chapter the currently used standard UHF RFID reader has been examined for its usage in sports timing. Analyzed is in what manner this reader inventories the individual tags in the field. Discussed is which parts of the algorithm could be a benefit for the sports timing optimized reader and which parts have negative effects on sports timing. First the general idea of the algorithm is explained. Secondly some individual components of the algorithm are explained in more detail. At last the algorithm is tested with a simulator and an evaluation is given.

Detailed part is removed (Confidential)

5-4 Optimizations for sports timing

Part is removed (Confidential)

5-4-1 Simulation results

The performance of the standard UHF RFID reader and the optimized reader for the purpose of Sports Timing is obtained with a simulator. The simulator is explained more deeply in chapter 6. Two races are simulated: Valencia and Boston. For both races a start and a finish. Furthermore are the algorithms simulated with and without taking into account the body influence. The human body affects the antenna signal, causing random noise and bad antenna reception. The performance is split in three parts: accuracy, efficiency and detection. The results for both readers are given in Figure 5-10.

The accuracy of a registered time is indicated by the number of hits. Or in other words: the number of reads per athlete for a single recorded time. The more often an athlete is seen, the more precise is the registration. The average number of hits is equal to the total number of successful readings divided by the total number of athletes. The better an algorithm adapts its frame size to the number of athletes currently in the field, the more hits are obtained. When the number of athletes in the field is low, each athlete can be read more often. This is why the number of hits is way higher at the finish than at the start. Furthermore do inefficient use of commands result in more overhead, a lower reading rate and a lower mean value of hits.

The slot efficiency gives an indication how efficient the radio channel is used. It is the percentage of slots filled with reads out of the total passed slots. A high efficiency corresponds to good adapting algorithm and an algorithm which has most of the time an optimal frame size. Normally an algorithm with high efficiency has also a high value of hits per athlete. However, the efficiency does not take into account the time wasted due to overhead. The efficiency gives therefore a better indication for the dynamic behavior of the algorithm than the average number of hits. The maximum expected efficiency is given in Figure 5-1. The maximum efficiency can be higher when the number of athletes is low. In example it could be 100% if there is only one athlete and no other athletes at the same time in the field. For higher numbers of athletes the efficiency converges to 36.8%. For that reason finishes have most of the time a better efficiency that starts.

The detection performance is an indication for the number of athletes that could be missed during a race. The detection performance is the percentage of missed athletes out of the total number of athletes that crossed the timing line. The probability for missing an athlete is higher when a start or finish is busier. The Valencia Start was really busy and has for that reason a low detection performance. In theory the detection performance is no issue for the reader when the density is low. Table 4-2 confirms this statement: when the number of athletes is low, no difference is found between the for throughput optimized backup line and the for more accuracy optimized main line. Furthermore does noise (human body influence) affect the antenna signal and the readability of a tag. In worst case an athlete is missed. For that reason the simulations with the human body influence enabled have also a low detection performance.

The results in Figure 5-10 show that the optimized reader performs better in all three parts. Efficiency is increased up to 10 times. The accuracy is improved with up to 1.4. And the most important improvement is the detection performance. Even at one of the busiest starts in the world, the Valencia marathon, 99.4 percent is detected. That is 2.3 percent more detections than the currently used standard reader.

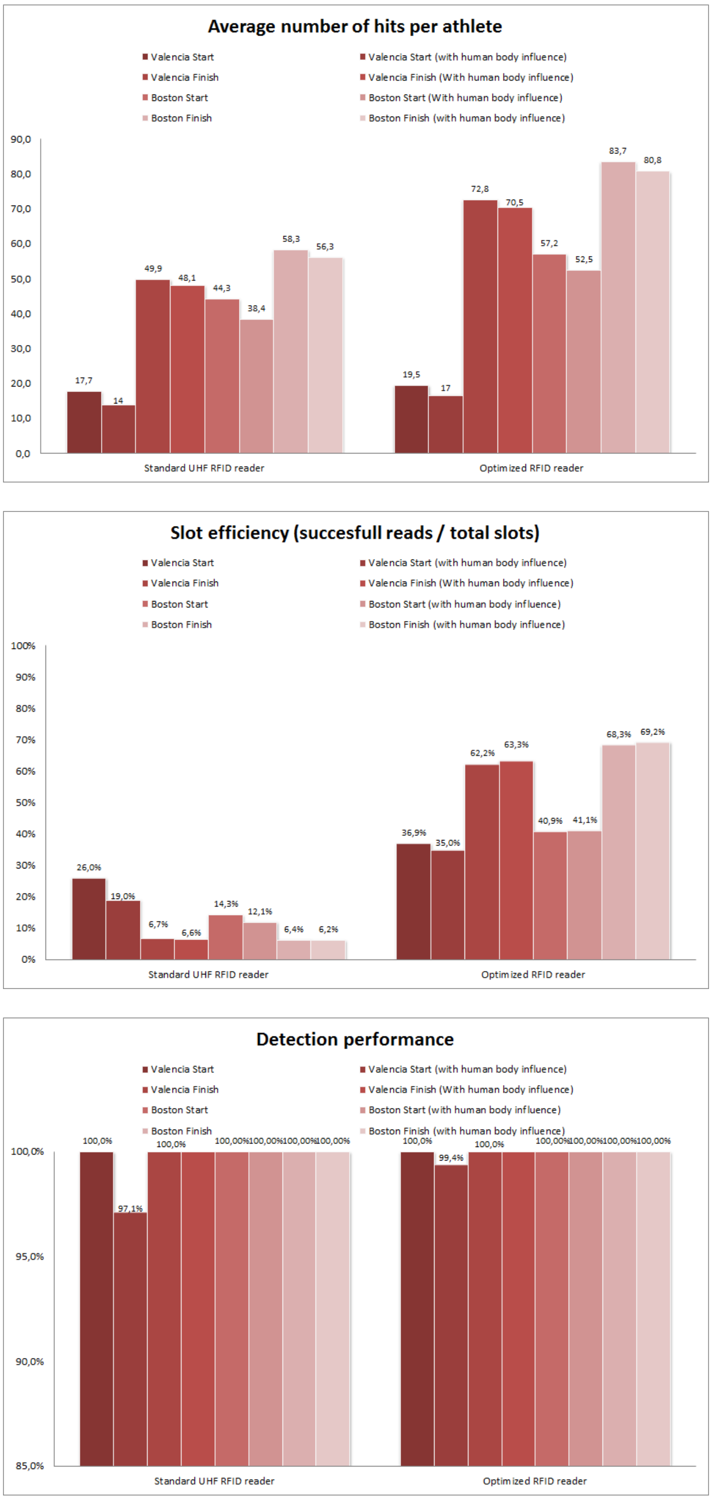


Figure 5-10: Simulation results: Standard UHF RFID reader vs Optimized reader

Chapter 6

Simulator

The algorithms proposed in 5-2-2 are tested for the suitability of sports timing with a simulation. A model of the BibTag system is made and the proposed reader algorithms are simulated with original race data. The simulator is able to import a marathon race and replays the race with a preselected algorithm. At the end of the race the overall performance of the algorithm is given. By replaying several algorithms with the same race data and conditions, a clear comparison of the algorithms can be made. In the next section is an overview of the simulator given. Secondly the antenna field of the simulator is clarified. And at last the timing and verification of the algorithm are described.

6-1 Overview of the simulator

In this section an overview of the simulator and its functionalities are given. A simplified presentation of the control flow is shown in Figure 6-1. Athletes enter a running field at predefined times and move in this field every time iteration. After each movement the strengths of the antenna signals are updated for each athlete as explained in section 6-2. When the strength of the backscattered antenna signal rises above the -65 dBmW, then the athlete enters the antenna range and the reader is able to communicate with the tag. The reader sends a command to all the tags within the antenna range according to the algorithm and the EPC Global Class1 Gen2 protocol [3]. Tags process these command according to the protocol [3] and could reply. The simulator then updates the performance statistics and increments the time. Again all athletes in the running field move to their new positions, new athletes may enter the running field and finished athletes may leave the field. This loop will continue till all athletes are finished and the race is over.

The Graphical User Interface is shown in Figure 6-2. In the middle of the screen is the running field. Athletes enter the running field from the right side and will leave the field at the left. The timing line is the middle of the running field. Four MYLAPS logos present the antennas. If the antenna is radiating, the logo is red colored, otherwise it is black. Athletes that are within the antenna range are colored. Four colors are possible: red, green, red glow

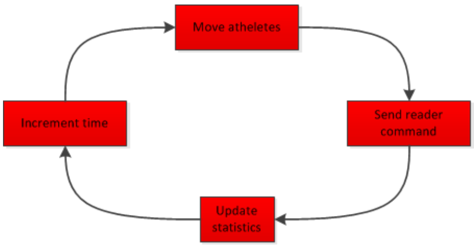


Figure 6-1: Simplified control flow

and green glow. A filled red or green color means that the athlete is invited by the reader and is participating in the inventory round. The athlete is green if it is already read in another round and red if not. A red and green glow means that the athlete is able to receive the antenna signals, but is not participating in the inventory round. In example when the reader has a different target (state A or B) or an athlete enters the antenna during a frame.

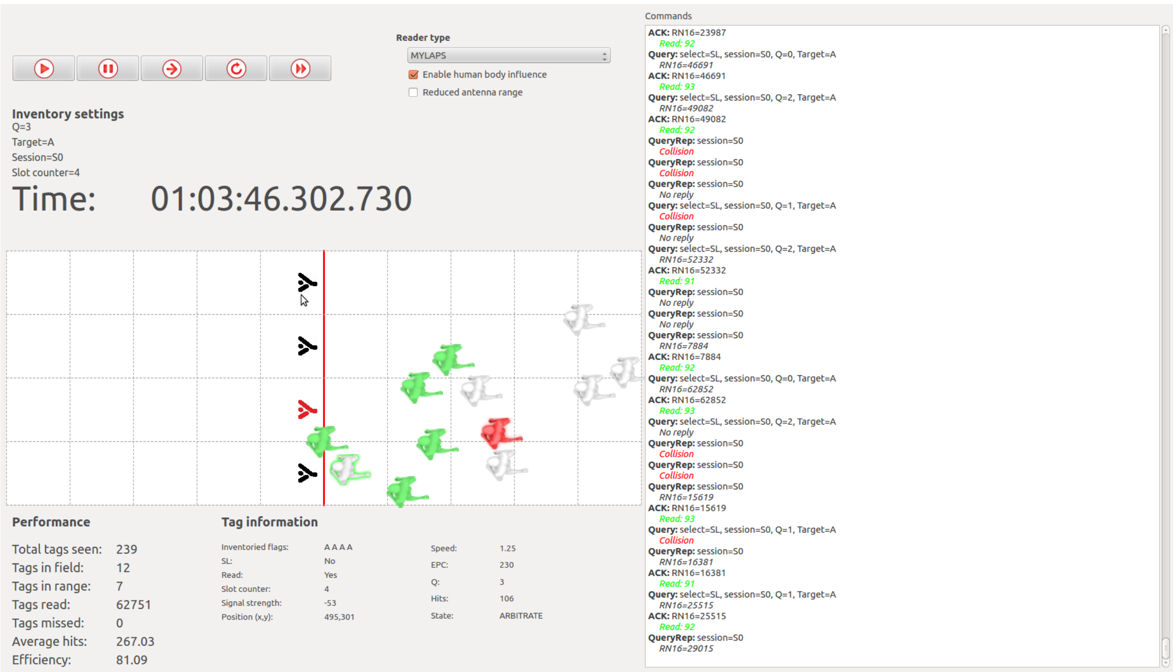


Figure 6-2: Graphical User Interface of the simulator

At the right side of the screen the reader commands are logged and the corresponding replies are shown. The user is able to follow the reader progress and can view the effects of a selected algorithm.

Below the running field are the statistics shown. The overall performance is displayed at the left side and detailed athlete information is displayed at the right side. By clicking on an athlete the detailed information updates.

The simulator is able to run at different control speeds. If a user wants to analyze a race in slow motion, then the race is updated step by step. It will stop after each command. Besides slow motion, the simulator can also run at normal speed or fast speed.

6-2 Antenna field

An important aspect of the simulator is the antenna field. The antenna field specifies the radiation pattern of the antenna and specifies the strength of a RF signal at all distances and positions. Since the tag backscatters its information to the reader with the original send carrier wave, the locations where the tag is able to communicate with the reader is determined by the strength of the radiated signal of the send antenna. In other words, the antenna field tells the simulator how many tags are able to communicate with the reader, for how long and with what signal strength. The antenna field is affected by its environment. For sports timing the human body has a huge influence on the antenna field. Athletes running between the send antenna and a tag placed on a chest result in a weaker RF signal.

6-2-1 Theory

The BibTag timing system has monostatic patch antennas. Transmission of a radio wave and the reception of its backscattered answer are done using the same antenna. For that reason the radio wave travels twice the distance between the tag and the antenna. In free space the path loss is then:

$$\text{Free-space path loss} = \left(\frac{4\pi f d}{c}\right)^4 \tag{6-1}$$

where f is the signal frequency, c is the speed of light in vacuum and d is the distance between the antenna and the tag.

Arriving signal strength higher than -65 dBmW can be read by the reader. The strength of received backscattered signal can be calculated with the following formula.

$$P_R = \frac{P_T G_A^2 G_T^2 c^4}{(4\pi f d)^4} \tag{6-2}$$

where P_t is the strength of the transmitted wave, G_A is the gain of the antenna mat in the direction of the tag and G_T is the gain of the dipole antenna of the tag. The transmitted power is approximately 30 dBmW and depends on the region and government regulations. The antenna gain depends on the angle between the tag and the antenna and the radiation pattern of the antenna. In best circumstances the antenna mat has a gain of 9 dBi. The antenna of the tag is a dipole antenna with a length of 0.5 Λ and has a gain of 1.64 (2.17dBi).

At last the calculation of the strength of the received signal has to be corrected for the polarization mismatch, the angle between the dipole antenna and the patch antenna and the signal loss due to the placement of the tag near a human body.

6-2-2 Experimental approach

Since the strength of the antenna is affected by a lot of (unknown) parameters, the antenna field of the simulator is not only based on the theory, but is also based on measured values. Backscattered signal strengths are measured on different distances away from the antenna. The tag was placed on a chest of a human body. Starting at the antenna measurements are

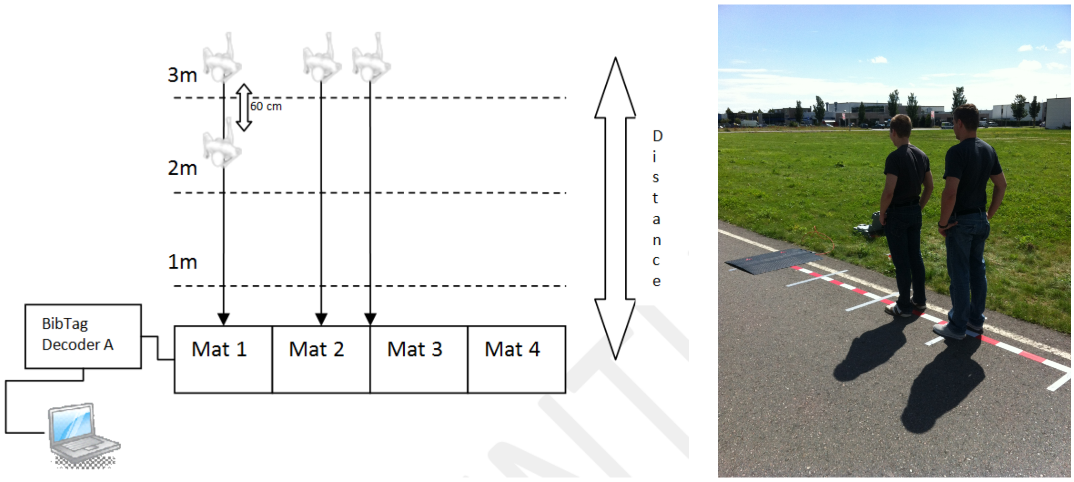


Figure 6-3: Test setup

performed with steps of 20 centimeter till the received signal was below -65 dBmW. The test setup is given in Figure 6-3.

The test results are given in Figure 6-4. The measured values confirm the statement of the line camera experiment in section 4-3-2 that the highest antenna strength (recorded time) is found half a meter before the antenna and not on top of the antenna. Normally the antenna gain and the signal strengths are at maximum on top of the antenna. However, the human body has influence on the antenna. For that reason the maximum antenna strength is found half a meter in front of the antenna. The experiment also shows that a correct placed tag is able to communicate with two or three antennas. Two if the athlete is running in the middle of two antennas and three if the athlete is running toward an antenna. In the latter situation are both neighbor antennas (left and right) able to communicate with the antenna.

At last but not least, the experiment shows the effect of another athlete that is running between the athlete and the antenna. On average the antenna signal is 12 dB less if another athlete is running in front of an athlete. However, due to the motion of the athletes the reduction varies between 4 and 20 dB. Simulations are run with and without the influence of other running athletes.

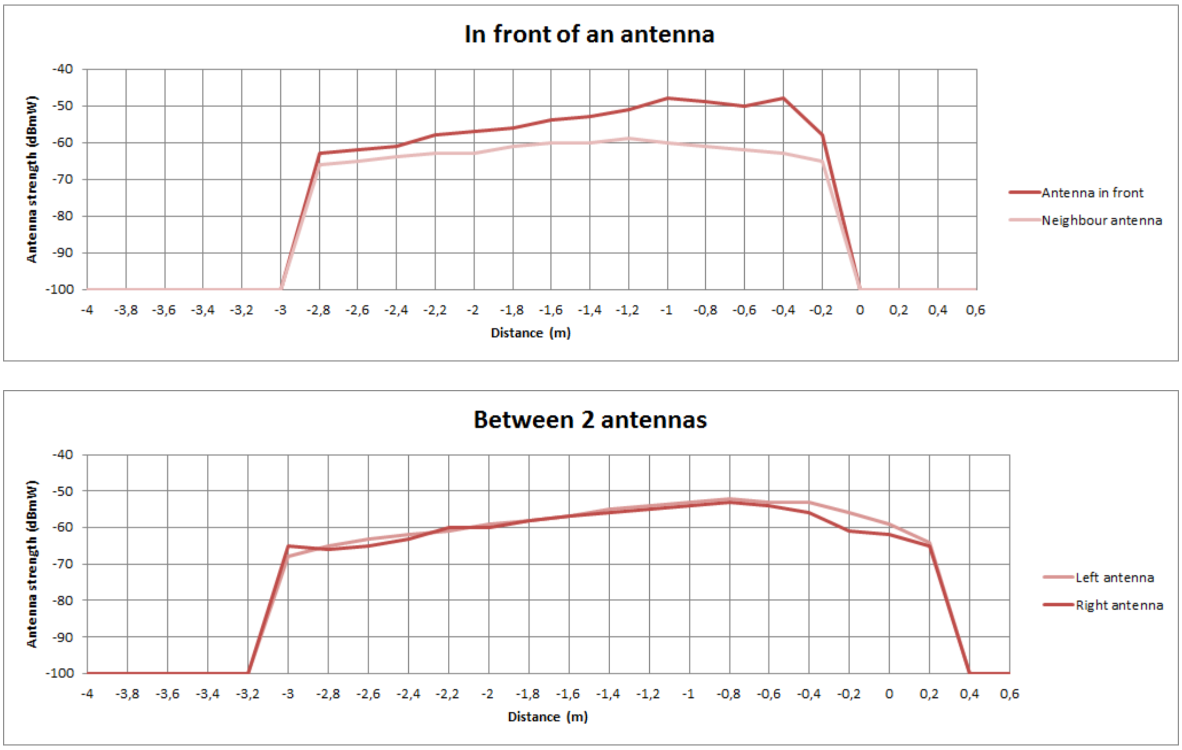


Figure 6-4: Antenna field measurements

6-3 Timing

The simulator makes use of the same timing settings as the original standard European reader. The standard European reader has the following characteristics.

Reader to tag communication:

- PR-ASK modulation
- Pulse Interval Encoding (20 μs)
- 865.7 MHz carrier wave

Tag to reader communication:

- Miller 4 encoding
- 274 kHz Backscatter Link Frequency

The duration of each command, the corresponding responses and times in between are measured with an oscilloscope. Communication between the reader and tag is recorded using a custom made tag. A photo of the test tag is given in Figure 6-6. This tag has a demodulator on board. Custom made software is able to set predefined tag responses and a preloaded communication scenario can be played and recorded in real time. An example of a reader to

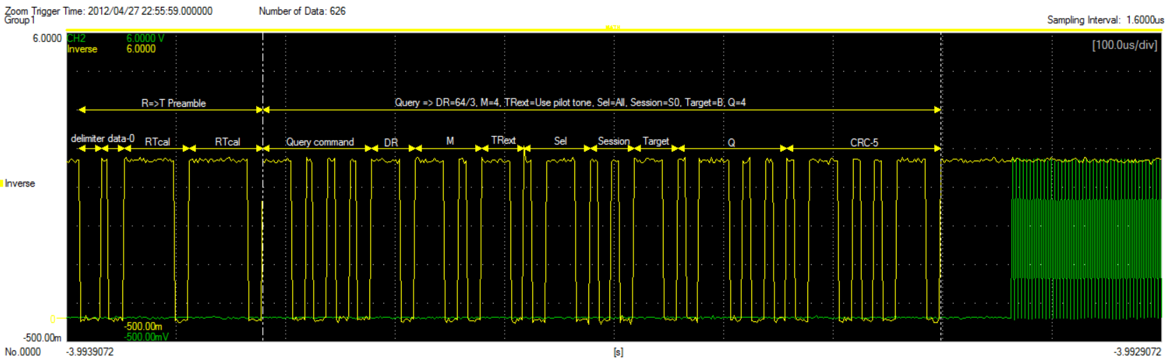


Figure 6-5: Timing of a query command

tag command is given in Figure 6-5. By loading a predefined scenario in the test tag, the timing of simulator is verified. Furthermore is the test tag used for monitoring the standard reader and for recovering the currently used algorithm.

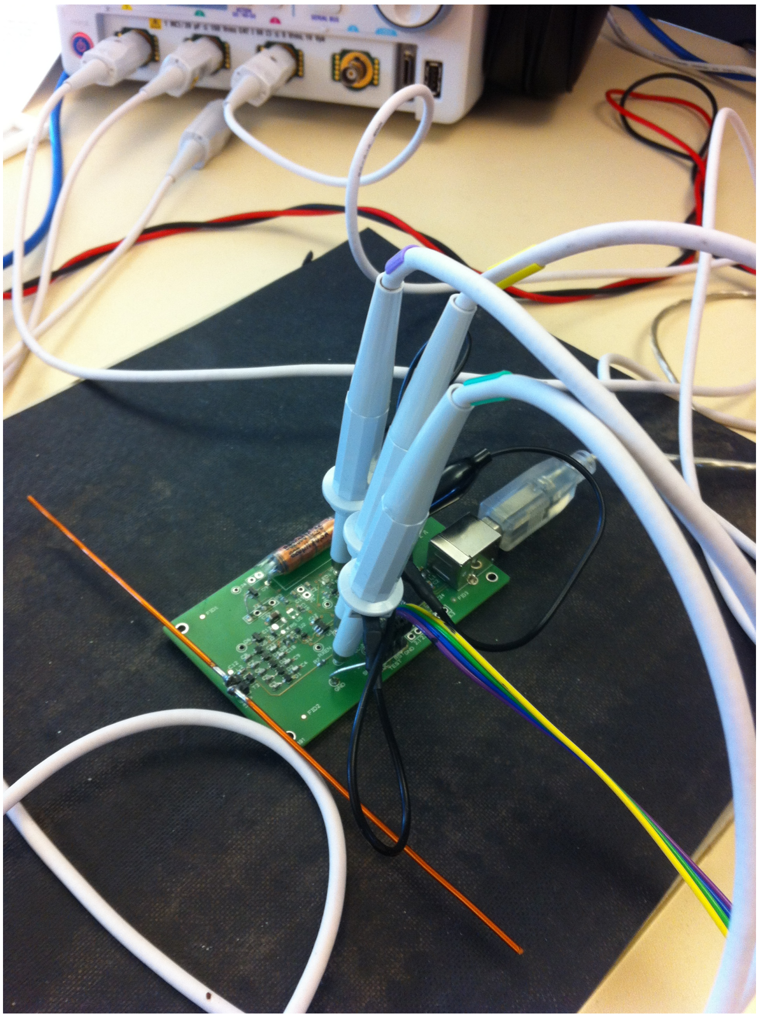


Figure 6-6: Custom made test tag

Chapter 7

Conclusion

A standard UHF RFID reader can be optimized for sports timing. A reader is optimized for sports timing if it follows two main goals:

1. read all unique tags, do not miss one
2. read all unique tags as many as possible

The optimized reader achieves these goals by using an advanced algorithm.

Detailed part is removed (Confidential)

This results in a faster antenna switching and a smaller probability of missing an athlete. The optimized reader has more single detections per athlete while crossing a timing line, resulting in a more accurate registered time. Simulation results show that the number of single detections per athlete is more than when a standard UHF RFID reader is used. The number of missed athletes is decreased.

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