Design and Implementation of Anti-collision Algorithms for Dense RFID Systems

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Abstract

Radio Frequency Identification (RFID) is a rapidly emerging technology that wirelessly transmits the identity of transponders (tags) attached to an object or a person. The RFID technology took more attention since the adoption of the EPCglobal Class 1 Gen 2 standard in 2005. It has replaced other automatic identification systems like barcodes in some applications, e.g. logistics. In such applications, the identification time is very critical performance parameter. Currently, developments are underway in various areas of RFID to decrease the total identification time for a massive number of tags. The present thesis focuses on passive Ultra High Frequency (UHF) RFID, whose transmission on the Medium Access Control (MAC) layer is scheduled by Framed Slotted Aloha (FSA). Conventional FSA regards only the reply of a single tag as a successful slot. Empty and collided slots are considered as losses. Therefore, the reading efficiency is limited due to empty and collided slots. Modern physical layer systems have the capability of converting part of the collided slots into successful slots. This is called Collision Recovery. Moreover, modern RFID readers can identify the type of slot, e.g., successful, collided, or empty. In addition, the readers are able to terminate a slot earlier upon recognizing that it is empty. The performance of such systems depends strongly on two main parameters: The precise estimation of the number of tags in the reading area, and the optimizations of the FSA frame length.

In this thesis, a new tag estimation method is introduced, taking into consideration the collision recovery capability of modern RFID systems. The proposed method provides the advantage of giving a novel closed form solution for the tag population estimator, which considers the collision recovery probability of the used system. Simulation results indicate that the proposed solution is more accurate when compared to state-of-the-art.

Apart from that, closed form solutions for the optimum FSA frame length for different scenarios are calculated. The first scenario is the Time-Aware Framed Slotted ALOHA. It considers the differences in slots durations without collision recovery capability. The second scenario is the Time-Aware with constant collision recovery coefficients system. This proposal provides a new closed form equation for the frame length considering the different slot durations and the collision recovery capability with equal coefficients. Moreover, a new calcu-

lation method of the collision recovery probability per frame is presented. In the third scenario, the multiple collision recovery coefficients system is introduced. There, the differences in the collision recovery probability coefficients are examined with equal slots durations. In this regard, the values of the collision recovery coefficients are extracted from the physical layer parameters. Finally, a Time-aware and multiple collision recovery system is suggested, considering the multiple collision recovery probability coefficients in addition to the different slot durations. For each scenario, timing comparisons are presented in the latter simulation results show the reading time reduction using the proposed frame length compared to other the state-of-the-art algorithms.

This thesis focuses on the EPCglobal C1 G2 standard. Therefore, the tags cannot be modified, and all the improvements are done only on the reader side. However, due to the limitation of the EPCglobal C1 G2, there is still a room of improvement between the proposed solutions and the theoretical lower bound of the identification time. Accordingly, compatible improvements of the EPCglobal C1 G2 standard are proposed. This proposal includes compatible modifications in the UHF RFID tags/readers, to be capable of acknowledging more than a sole tag per slot. Finally, the obtained results demonstrate that the proposed system optimizations lead to identify tags in significantly shorter time, which is crucial for time-sensitive applications.

Contents

Chapter 1

Introduction

Radio Frequency Identification (RFID) is a technology that uses communication through radio waves to transfer data between a reader and electronic tags attached to an object, either to be identified or tracked. The RFID technology has benefits in reference to other identification technologies [1], such as no line-of-sight connection, fully automotive identification process, robustness, identification speed, bidirectional communication, reliability in different environment conditions, bunch detection and secured communication. Thus, RFID became the optimum solution for several applications where other identification technologies like bar-codes are unsuitable, for example, inventory tracking, supply chain management, automated manufacturing, etc [2–4]. Due to the crucial significance of the RFID system in different real-world applications, RFID systems have received large attention from both, research groups and industry. Recently, many work has been published on the area of RFID systems whether in hardware and software design, or in protocols and applications, etc [5–7]. This chapter will present the research motivation along with the thesis contributions and outline.

1.1 Motivation

During the past few years, the number of applications that use RFID has increased, and their number will potentially further grow in the near future. One of its main applications is logistics, where, for example, many tags (transponders) may be closely placed on pallets. Thus, in such systems, we have a single

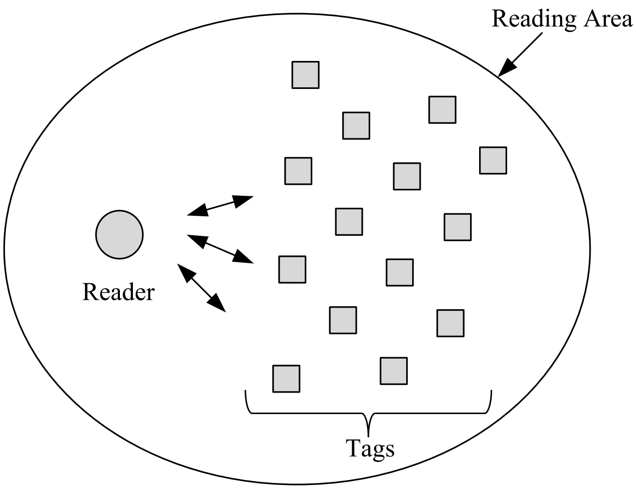


Figure 1.1: Dense RFID network with single RFID reader

RFID reader that is responsible for identifying an unknown number of tags in the reading area as shown in figure 1.1. This naturally requires fast RFID readers (interrogators), in order not to slow down the delivery process of the actual goods. According to [8–10], the EPCglobal C1 G2 [11] is the most commonly used RFID standards in logistics. It is based on Time Division Multiple Access (TDMA), which leads to a certain probability of tag-collisions on the communications channel. Owing to their low price and simple design, tags can neither sense the channel nor communicate with the others. Hence, the readers are responsible for coordinating the network, and avoiding collisions using anti-collision algorithms.

According to the previously published RFID work, Frame Slotted ALOHA (FSA) [12, 13] is the most widely used Medium Access Control (MAC) anti-collision protocol for RFID systems due to its simplicity and robustness. In FSA, the communication timing between the reader and the tags is divided into TDMA frames, each frame includes a specific number of slots. The frame length is a function of the existing number of tags in the reading area. During the reading process, each active tag randomly assigns itself to one of the available slots in a frame. Therefore, each slot can take one of three different states: 1) Successful Slot: Only one tag chooses this slot, is fully identified, and then deactivated by the reader. 2) Collided Slot: Multiple tags reply, resulting in a collision. The collided tags normally remain in their active state and retry their transmission in the next frame. 3) Empty Slot: No tag responds and the slot remains unused. Therefore, the reading efficiency is limited by the effect of two main parameters:

1. The accuracy of the FSA frame length: If the frame length is higher than the optimum value, many empty slots in this frame will be present, which reduces the reading efficiency. If the frame length is lower than the optimum value, this will result many collided slots, which again reduces the reading efficiency. Thereby, choosing the optimum value in FSA frame length is the most crucial optimization parameter in such application.

2. The robustness of the number of tags estimation: The optimum FSA frame length strongly depends on the actual number of tags in the reading area. However, in real-world applications, the number of tags of the reading area is unknown. Therefore, the more precise the number of tags estimation, the better the reading efficiency.

Recent research groups have focused upon using the PHY (Physical) Layer properties, in the so-called Collision Recovery phenomena, to convert part of the collided slots into successful slots [14, 15]. This decreases the losses which result from collisions. Moreover, modern RFID readers have the ability to identify the type of the slot (successful, collided, or empty). Thus, the RFID readers are able to terminate the slot earlier as soon as they recognize the absence of a tag reply [16, 17], which eliminates the effect of the empty slots.

According to the previous discussion, the number of tags estimation algorithm and the optimum FSA frame length strongly depend on the PHY-layer properties of the used system.

1.2 Thesis Contribution

This thesis aims to improve the performance of existing UHF RFID systems, mainly by minimizing the total identification delay. The accomplished work focused on optimizing the FSA frame length and the number of tags estimation algorithm for dense RFID networks, taking into consideration the MAC/PHY-layer parameters. All modifications are on the reader side, as the improved system has to follow the EPCglobal C1 G2 standard [11]. Moreover, results are compared to the theoretical lower limit for this standard. Finally, compatible upgrades of the EPCglobal C1 G2 standard are proposed, thus granting additional improvements for the overall performance. The main contributions of this thesis can be summarized as follows:

1. A number of tags estimation method is developed, taking into consideration the collision recovery capability of the physical layer. The main advantage of the proposed method is that it provides a new closed-form solution for the tag population estimator, which considers the collision recovery probability of the used system. Simulation results indicate that the proposed solution is more precise compared to the state-of the-art. Timing comparisons presented in the simulation results show the reduced identification delay of the proposed estimation method compared to other proposals.

2. A closed-form solution for the optimum frame length for FSA is provided by optimizing the Time-Aware Framed Slotted ALOHA reading efficiency, which considers the differences in the slot durations. The simulation results indicate that the proposed solution gives the most accurate results with respect to the exact solution.

3. Another closed-form solution for the optimum frame length for FSA is settled by optimizing the Time and constant collision recovery coefficients aware reading efficiency. The proposed solution gives a new closed form equation for the frame length considering the different slot durations and the collision recovery capability with equal coefficients. Moreover, a new method was introduced to calculate the capture probability per frame. Simulations indicate that the proposed solution gives accurate results for all relevant parameter configurations without any need for multi-dimensional look-up tables.

4. A new closed-form solution for the optimal FSA frame length is established, which considers the differences in the collision recovery probabilities. The values of the collision recovery coefficients are extracted from the physical layer parameters. Timing comparisons are presented in sim-

ulation results to show the mean reduction in reading time using the proposed frame length compared to other proposals.

5. Further, a new closed-form solution for the optimal Frame Slotted ALOHA (FSA) frame length is created. The new solution considers the multiple collision recovery probability coefficients, and the different slot durations. Timing comparisons are presented in the simulation results to show the reading time reduction using the proposed frame length compared to other the state-of-the-art algorithms.

6. Finally, compatible improvements of the EPCglobal C1 G2 standard are proposed. They require some compatible modifications in the UHF RFID tags/readers, to be capable of acknowledging more than a single tag per slot.

1.3 Document Outline

A brief outline of this document is presented as follows. Chapter 2 introduces the historical background and literature survey of RFID systems. Chapter 3 presents the collision problem in the RFID systems and the existing anti-collision algorithms. Moreover, the concept of proposed cross-layer anti-collision algorithm will be defined. Chapter 4 reports the most commonly used number of tags estimation algorithms in the RFID system. Afterwards, the proposed collision recovery aware maximum likelihood estimation algorithm is discussed. In this part, a closed-form solution for the estimated number of tags in the reading area is suggested taking into consideration the collision recovery capability of the used system. Chapter 5 shows different case studies for FSA frame optimization. Each case depends on the PHY-layer parameters. Hence, in every case, a closed-form solution for the optimum FSA frame length is an analytically derived function of the estimated number of tags and the PHY-layer parameters. Chapter 6 provides compatible improvements of the EPCglobal C1 G2 standard. In this system, such modifications to tags/readers, can acknowledge more than a single tag per slot. Finally, chapter 7 sums up the thesis by highlighting the main issues addressed in this thesis and outlining some of the future research aspects.

Chapter 2

Introduction to RFID

This chapter provides an overview of the historical development of RFID. In addition, it describes the basic principles and the major technical aspects related to the RFID technology and its standardization. By the end of this chapter, the major issues in dense networks will be presented.

In section 1 an overview is given about the historical development of RFID. Secondly, section 2 will present the main components of the system followed by section 3 in which the operating frequency bands in RFID will be shown. Afterwards, the classification of the RFID standards will be presented in section 4. Finally, section 5 describes the RFID collision problem.

2.1 Historical Development of RFID

In the year 1935, the first notion of RFID system was invented by a Scottish physicist called Robert Alexander for detecting aircraft [18]. Next, in 1950, the British government developed the first prototype of the RFID system, which is known as Identification Friend or Foe (IFF) system [19]. This system was designed for aeronautical applications. Between the 1950s and 1960s, there was a big development in the RFID systems for different applications, e.g. the application of the microwave [20] and radio transmission systems that modulate passive responders [18]. In the 1970s, RFID was intensively applied to logistics, transportation, vehicle tracking, livestock tracking as well as industrial automation. The first US patent in this field was published in 1973 for the invention of an active RFID tag with re-writable memory [19]. Nowadays, the low power ultra high frequency (UHF-RFID) system research has gained certain importance. In 2008, the US Department of Defense have announced that they plan to use electronic product code (EPC) [1] technology to track goods in their supply chain. In Europe, RFID was intended to improve industrial applications and to enable short-range systems for animal control [20]. In Japan, RFID was used for contact-less payments in transportation systems [18].

2.2 System Components

As shown in figure 2.1, conventional RFID systems consist of three main components: RFID tags or transponders which are attached to the object requested to be identified or tracked. RFID reader and antennas which control data transmission and the whole identification process. Processing device commonly called Middle-ware. It is always a software processing device. All the external processing depending on the application is done on this device using the EPC code which is identified by the reader from the tag. In the following sections, each component will be described in detail.

2.2.1 Tags

The tag is the device, which is attached to the object. It stores information and might be incorporated to sensors. This information includes their unique EPC, which is a standardized identification code. When tags are within the reading range of the reader, they receive a command from the reader asking them about their EPC. They reply with their identification data to the reader, which processes the information according to the current application. Generally, RFID tags are divided into the following categories:

Passive tags Passive tags are the most commonly used tags in tracking and supply chain markets [21, 22]. They are extremely simple and inexpensive devices (less than 0.10 €). Passive tags do not contain any power source so they derive all of the required energy for their operation from the signals emitted by the reader. This energy activates the circuit of the tags. Then, they send a reply signal that includes their information. The maximum communication

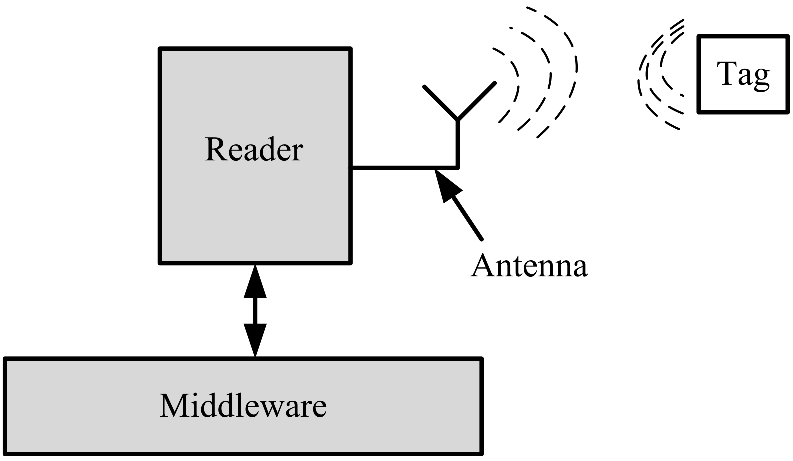


Figure 2.1: Main UHF RFID system components with single reader and backscatter UHF tag

range is up to a few meters.

Active tags Active tags are the second commonly used type of tags. They have a fully autonomous power source [23,24]. These devices are more expensive than passive ones (starting from 10 €) because they incorporate circuits with a microprocessor and a memory to read, write, rewrite or erase data from an external device. However, there are several advantages of active tags compared to the passive ones. Among them, active tags support long reading distance, i.e. more than 100 meters. In addition, they also support immunity to the interference especially in harsh environment e.g. environments with excessive amounts of metals, such as shipping containers. Owing to their power supply property, they are easily connected with sensors, thus, monitoring the environment depending on the application e.g. food or drug shipments.

Semi-passive tags In semi-passive tags, batteries are used on board to power the controller or the chip and may contain additional devices such as sensors [25,26]. The signals, which are generated by the reader are only used to activate tags in coverage. Then, the tag's reply is generated using the energy emitted from the internal batteries. Semi-passive tags can communicate over longer distance than the normal passive tags. Moreover, the circuitry activation of the semi-passive tags is faster than in passive tags.

2.2.2 Readers

The RFID reader is the most important element in an RFID system [23]. It is responsible to access the tag information. The reader decodes the received data from the tags then sends this information to the middle-ware. The reader performance depends strongly on two factors: First, the decoder architecture. Second, the antenna design.

Decoder architecture Readers can be classified according to the type of tags as follow:

Readers dealing with active tags In active RFID systems, since active tags are able to initiate the communication between them, any active tag can act as a reader. However, when active tags act as a reader, they must be connected to a computer or a network (via a wired or wireless link) to send the received data from its network [22].

Readers dealing with passive tags They must meet the following key requirement: Their transmission power must be sufficient to feed the surrounding passive tags [13]. These tags obtain energy from the transmitted signal using back-scattering technique. Back-scattering technique is the reflection of the reader's carrier wave where it modulates the signal which includes the tag's data. Then, the reader detects the tag's response, processes the signal and reads the information sent by the tag.

Antennas Antenna designs are strongly dependent on the operating frequency [27]. In case of low range applications, such as LF (125 kHz) or HF (13.56 MHz) range, antennas are embedded in the readers. However, in case of UHF applications, antennas have to be external. Moreover, polarization of the used antenna is one of the most critical issues. Antenna polarization affects directly the RFID system performance. In RFID systems, there are two types of antenna polarization:

Linearly polarized antennas Using these antennas, the electrical field component of the transmitted signal is propagated in a plane, and tags have to be also orientated in the same direction of the transmitted signal [28]. For optimum receiving efficiency, this technique requires linearly polarized tags.

Circularly polarized antennas Using these antennas, the electromagnetic waves are transmitted in circularly polarized patterns. This type of polarization is used when the orientation of tags with respect to the reader cannot be controlled. Using circularly polarized antennas, a communication with both, linearly and circularly, tags can be established. However, circularly polarized antennas have a shorter reading range compared to the linearly polarized ones [29, 30].

2.2.3 Middle-ware

In some applications, the tag identifier is used as an input for a database to get an information related to this object e.g. shipment orders, expiring date, etc. This kind of processing is done in a set of software tools called middle-ware. The EPCglobal standards [11] define specifications for the middle-ware of RFID systems. Meanwhile, RFID systems are still an evolving technology. Thus, RFID middle-ware should be flexible enough so that it could be adapted to the future changes with minimal efforts.

2.3 Frequency Bands

The most important differentiation criteria for RFID systems are the operating frequency of the reader. Selecting the most adequate frequency is a function of the following properties:

- Technical properties of the application e.g. The RFID channel contains metals or not.
- Cost of the system.
- Behavior of the electromagnetic waves at these different frequencies.

First RFID systems started with Low Frequency (LF) band RFID systems [31]. After few years, the RFID systems have operated in High Frequency (HF)

Table 2.1: Frequency Bands for RFID Systems [32]

Frequency Band	Range	Common Frequencies
Low Frequency (LF)	0.5 m	125 kHz, 134.2 kHz
High Frequency (HF)	$1-3$ m	13.56 MHz
Ultra High Frequency (UHF)	10 m	866 MHz Europe 915 MHz USA
Microwave (μW)	>10 m	2.45 GHz, 3.0 GHz

band [32]. Using only these two band made a big limitation on the RFID applications. Thus, Recent years, the number of RFID systems operating in the Ultra High Frequency (UHF) range have increased because of the dramatic decrease in its component's price [33]. Thus, it is expected to see the RFID microwave band more available and affordable in the market. The availability of all bands with affordable costs will give the RFID users more facilities to take easier decision in which band they need to build up their applications.

Table 2.1 presents the most common frequencies for each band as well as the maximum allowed distance for each band. It is necessary to note that Table 2.1 does not present the only possible operating frequencies. It presents only the most commonly used frequencies in each band. Thus, it is possible to find systems operating at different frequencies, within each frequency band. This thesis focused upon the UHF frequency band, because it is suitable for the passive dense RFID applications.

2.4 RFID Communication Standards

There are different standards of the communication between the RFID reader and the corresponding tags. Although the EPCglobal C1G2 standard is the most extended and adopted for passive dense RFID networks, yet, there are further other standards. Table 2.2 shows the most common RFID standards with a short description for each one. This thesis discusses the Generation 2, Class 1 standard, because it is the most suitable standard for dense RFID network, as the cost of the system is ideal for such applications.

Table 2.2: RFID standards classification [11]

Standards Classification	Description
Generation 1, Class 0	Read only passive tags Unique EPC programmed in the factory
Generation 1, Class 0+	Identical to the normal Generation 1, Class 0 tags Tags can be programmed by users
Generation 1, Class 1	Similar to Generation 1, Class 0 or 0+ tags Identified by readers from different companies
Generation 2, Class 1	Faster data rates then Generation 1 tags Rewritable memories
Generation 2, Class 2	Similar to Generation 2, Class 1 tags
	More noise immunity
Generation 2, Class 3	Semi-passive or battery assisted tags
Generation 2, Class 4	Active tags
Generation 2, Class 5	Active tags Capability to power on other tags

2.5 Collision Problems

In RFID systems, both readers and tags communicate using the same frequency. Thus, simultaneous transmission could happen that leads to collisions. Collisions destroy the identification number EPC of the tag and may also interfere control commands of the readers. Thereby, the collision problem is the main source of delays in the identification process. There are two types of collisions: reader collisions and tag collisions. The following sections describe in details both types and how each of them affects the performance of the system.

2.5.1 Readers Collisions

There are two main types of readers collisions or interference in RFID systems: multiple readers to tag collision and reader to reader collision.

Multiple Readers to Tag Collisions: Multiple readers-to-tag collisions occurs when one tag is simultaneously located in an overlapped area between two neighbor reading areas [34, 35], and both readers communicate simultaneously with the shared tag as shown in figure 2.2. In this situation, the tag will not be able to determine such communication, due to the interference between the two

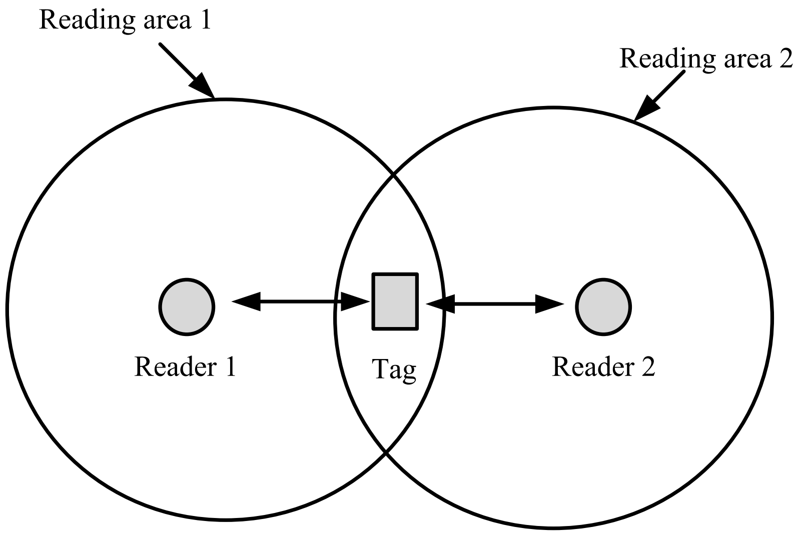


Figure 2.2: Multiple readers to a single tag collision

readers commands. Therefore, the tag will not respond to any readers. Finally, this slot would be an empty one leading to losses in the total identification time.

Reader to Reader Collisions: Reader-to-reader collisions, or interference, occurs when the signal generated by a reader acts as a jamming signal for a neighbor reader as shown in figure 2.3. This signal might prevent the second reader from communicating with its tags in its reading area [36, 37]. Such interference can occur even if there is no overlapping area between the reading areas. This interference affects the total identification time of the interfered system.

2.5.2 Tag Collisions

This type of collision is the most common type of collision in dense RFID systems [38–41]. In such systems, we have a single RFID reader and multiple tags as shown in figure 2.4. The main objective is to identify all tags in the reading area in the minimum possible time. However, in dense networks, the number of tag collisions increases, which decreases the reading efficiency, and hence increases the reading time. Different research groups are currently associated with how efficiently develop an anti-collision protocol for such systems.

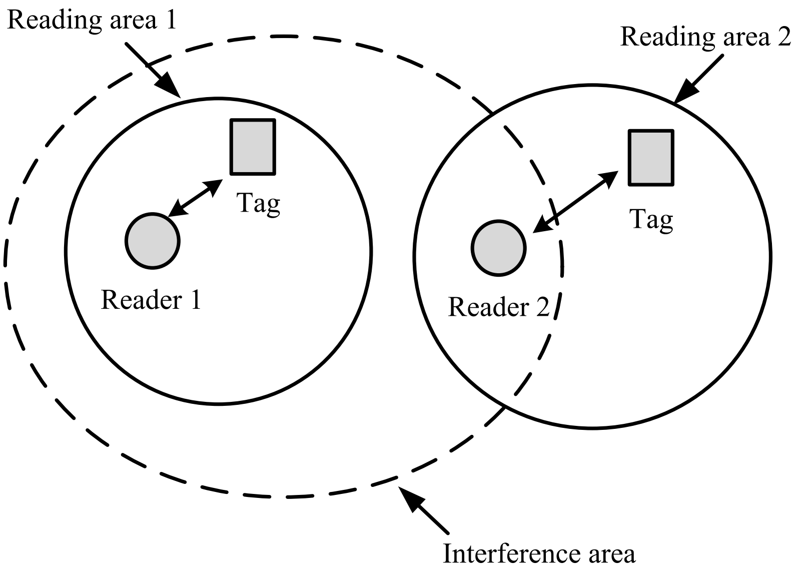


Figure 2.3: Multiple readers interference

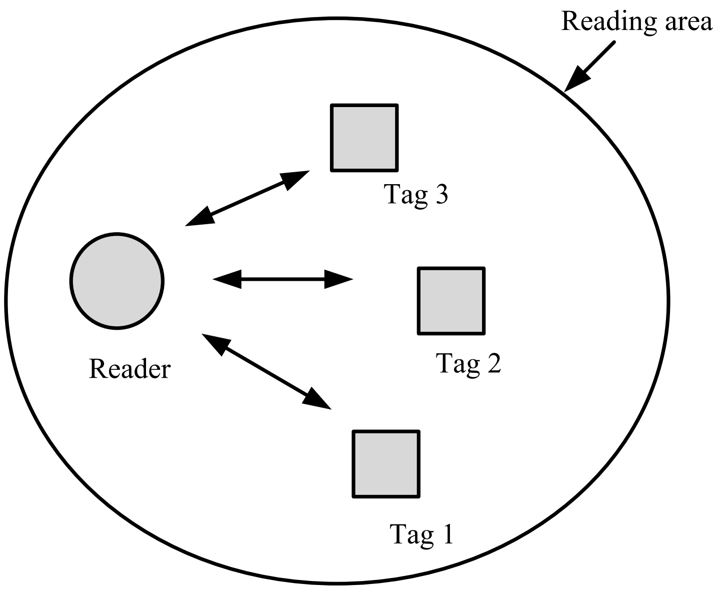


Figure 2.4: Multiple tags to a single reader collision

Table 2.3: RFID standards classification [11]

Standards Classification	Description
Generation 1, Class 0	Read only passive tags Unique EPC programmed in the factory
Generation 1, Class 0+	Identical to the normal Generation 1, Class 0 tags Tags can be programmed by users
Generation 1, Class 1	Similar to Generation 1, Class 0 or 0+ tags Identified by readers from different companies
Generation 2, Class 1	Faster data rates then Generation 1 tags Rewritable memories
Generation 2, Class 2	Similar to Generation 2, Class 1 tags
	More noise immunity
Generation 2, Class 3	Semi-passive or battery assisted tags
Generation 2, Class 4	Active tags
Generation 2, Class 5	Active tags Capability to power on other tags

Anti-collision protocols can be classified into two main types: Physical layer protocols and MAC layers protocols. In this thesis, I am focusing on the applications which include only a single RFID reader and dense RFID tag populations. The main motivation of this thesis is to minimize the total identification time for a dense and passive RFID networks. Therefore, there are different proposals to solve the tag collision problem by enhancing the existing anti-collision protocols taking into consideration the physical layer parameters. Moreover, the applications of the dense RFID networks are following the EPCglobal C1 G2 standards [11]. Thus, the proposed improvements in this thesis are done only on the reader side. Finally, chapter 6 will propose slight modifications in the standard to have further improvements and, at last, compare the results against each other.

Chapter 3

RFID Anti-collision Protocols

This chapter presents the most common anti-collisions algorithms for passive RFID systems, either by using the physical layer or the MAC layer. It will emphasize the anti-collision algorithms which are compatible with the EPCglobal C1 G2 standard, as t is the main focus of this thesis.

This chapter is organized as follows: section 1 gives an overview about the physical layer anti-collision algorithms. In section 2, different MAC-layer anti-collision algorithms are presented, thus clarifying the main differences between them. Afterwards, a brief description for the EPCglobal C1 G2 reading process will be presented in section 3. Section 4 will give an introduction about the collision recovery and the slots duration in modern RFID readers and the effect of these parameters in MAC-layer anti-collision algorithm, which will be focused on, in the remaining part of this thesis.

3.1 PHY-Layer Anti-collision Protocols

Different physical layer anti-collision protocols have been developed to separate colliding signals on the physical layer. Figure 3.1 shows the most common physical layer anti-collision protocols, which are: FDMA, SDMA, CDMA and TDMA. These algorithms will be briefly discussed in the following paragraphs:

Frequency Division Multiple Access (FDMA): In this protocol, the frequency band is divided into different sub-frequency bands and tags are distributed among them [42]. However, this technique adds complexity to the

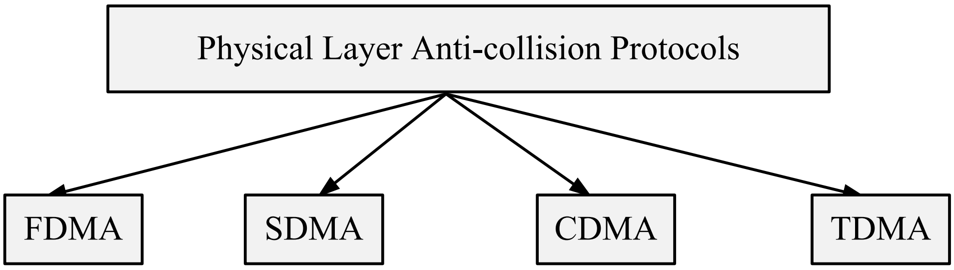


Figure 3.1: Common existing PHY-Layer anti-collision protocols

system. Readers should be able to decode different frequencies at the same time. Moreover, tags should be able to select its desirable sub-channel, which is incompatible with EPCglobal C1 G2. Only active tags can do such function.

Space Division Multiple Access (SDMA): This technique makes use of spreading tags over the reading area. It provides a high increase in the reading efficiency [43]. The main drawback is the cost of implementing the RFID reader with multiple antennas. Moreover, in dense applications, the distances between the tags is very small in order to be distributed on the reading area.

Code Division Multiple Access (CDMA): This protocol uses spread-spectrum modulation techniques to transmit the data over the entire spectrum [44]. CDMA is the ideal procedure for many applications, e.g. navigation systems. However in case of RFID systems, it is not compatible with EPCglobal C1 G2, as the cost of the tags will severely increase. Thereby, it is not a sufficient protocol within the scope of this thesis.

Time Division Multiple Access (TDMA): In this protocol, a single frequency band is divided to time slots and is assigned to tags. One of the most important features of this technique is that each tag must be synchronized to the time slots and send its information at the beginning of the selected slot [45]. This technique can be directly applied to passive RFID systems. In such systems, the simplicity of tags transfers the complexity to the readers, where the reader has to control the time synchronization. However, in active RFID systems, synchronization can be either centralized or distributed to the tags.

In UHF passive dense RFID system, both TDMA and SDMA are the most commonly used PHY-layer anti-collision protocols. In these systems, there is only a single reader versus a large number of tags. Thus, there is no problem to increase the complexity of the reader. However, the tags should be as cheap and simple as possible.

3.2 MAC-Layer Anti-collision Protocols

Unfortunately, the physical layer anti-collision proposals are not cost effective for the market challenges of the passive RFID technologies. Therefore, collision solutions are commonly implemented at the MAC-layer. This section will discuss the most common MAC-layer anti-collision protocols.

Figure 3.2 presents the main classification of the most common MAC-layer anti-collision protocols. According to figure 3.2, MAC-layer anti-collision protocols is classified into two main categories: deterministic protocols and probabilistic protocols. Deterministic protocols are used in systems with known number of tags to be identified in the reading area. These types of protocols are mainly based on tree algorithms for the identification processes. Probabilistic protocols are used in systems with an unknown number of tags. Probabilistic protocols are mainly based on ALOHA algorithm.

The following sections will discuss in details the most commonly used anti-collision algorithms either deterministic or probabilistic based algorithm.

3.2.1 Deterministic Anti-collision Protocols

These protocols are commonly named tree-based anti-collision protocols. Using these algorithms, the reader aims to identify a set of tags in the coverage area in subsequent time slots [46]. Each time slot contains a “Query” command, transmitted from the reader, and the response of tags in the reading area. If there is more than one tag reply in one slot, a collision occurs and the reader tries to split the tags into two subgroups. The reader repeats the splitting procedure until it receives a single tag reply. Tree based anti-collision protocols can be classified into two groups:

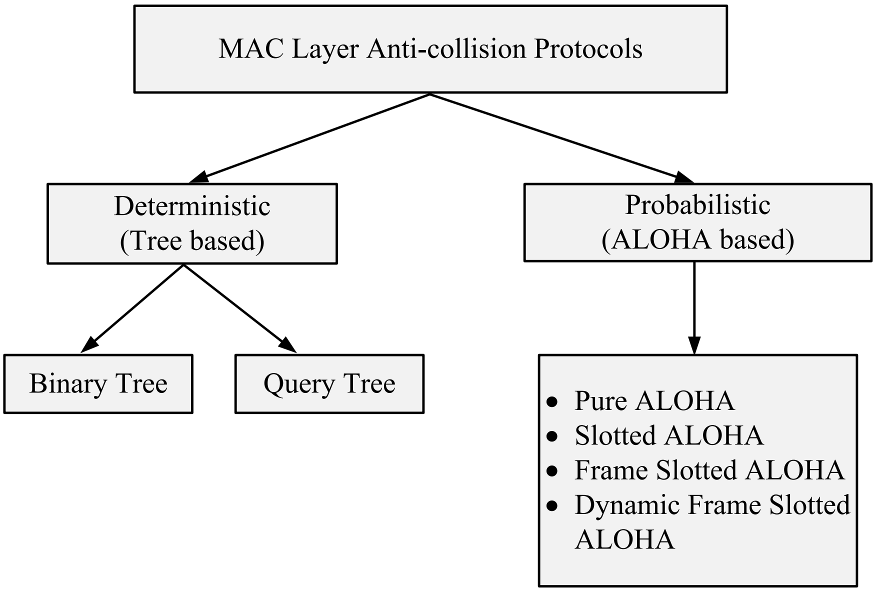


Figure 3.2: Common existing MAC-Layer anti-collision protocols

Binary tree

The binary tree algorithm [47] is commonly used in tree-based anti-collision protocols. Using this algorithm, if a collision occurs in a time slot, each collided tag selects randomly '0' or '1'. Thus, the colliding tags will be separated into two subgroups. Tags, that selected '0' always transmit their IDs to the reader first. If a collision re-occurs, collided tags are splitted again by selecting '0' or '1'. Tags, which have selected '1' have to wait until all other tags which have selected '0' are successfully identified by the reader. This procedure continues recursively until the subset is reduced to one tag, that is identified without collisions.

Figure 3.3 shows an example of the binary tree algorithm resolving the collision of four tags in a reading area. Thus, we have a collided time slot at the beginning. At time slot 2, each collided tag has to choose '0' or '1' randomly. In our example, tags 1 and 2 have selected '0'. However, tags 3 and 4 have selected '1'. According to binary tree algorithm, tags 3 and 4 have to wait until tags 1 and 2 are successfully identified. Therefore, time slot 2 is a collided slot due to the collision between tags 1 and 2. Due to collision, both tags 1 and 2 have to choose either '0' or '1'. In this example, both tags 1 and 2 have selected '1'. This resulted and empty slot in time slot 3 and collided

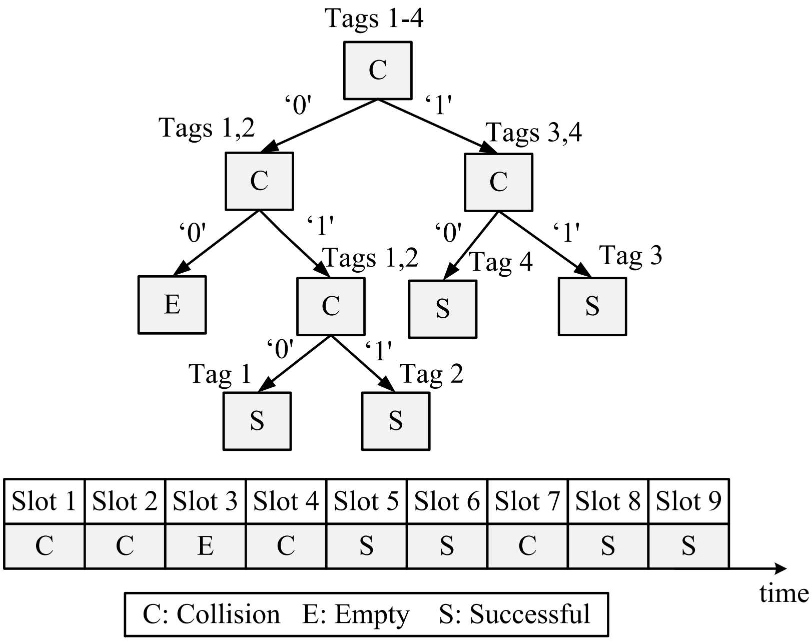


Figure 3.3: Binary tree anti-collision algorithm example

slot in time slot 4. Afterwards, tag 1 has selected '0' and tag 2 has selected '1'. This random selection made them separated and results in two successive successful slots in time slots 5 and 6. At this moment, tags 3 and 4 started their identification process. The reader repeats the previous process until identifying all tags in the reading area.

Query tree

Another category from tree algorithm is the query tree algorithm [48]. It is also commonly used in tree-based anti-collision algorithm. Using this algorithm, the broadcast is a query signal asking the tags for a reply. If there is a collision, it starts splitting the collided tags into two groups by sending a new query signal with a single bit 0 or 1 randomly. Tags in the reading area receive this signal and match this bit with their ID. If this bit matches their ID, they transmit their ID. If a collision happened again, the reader adds another random bit 0 or 1 to its next query signal. This process is repeated until the reader receives a successful single tag reply.

Figure 3.4 presents an example for the query tree algorithm resolving the collision of 4 tags in a reading area. At time slot 1, the reader broadcasts a query

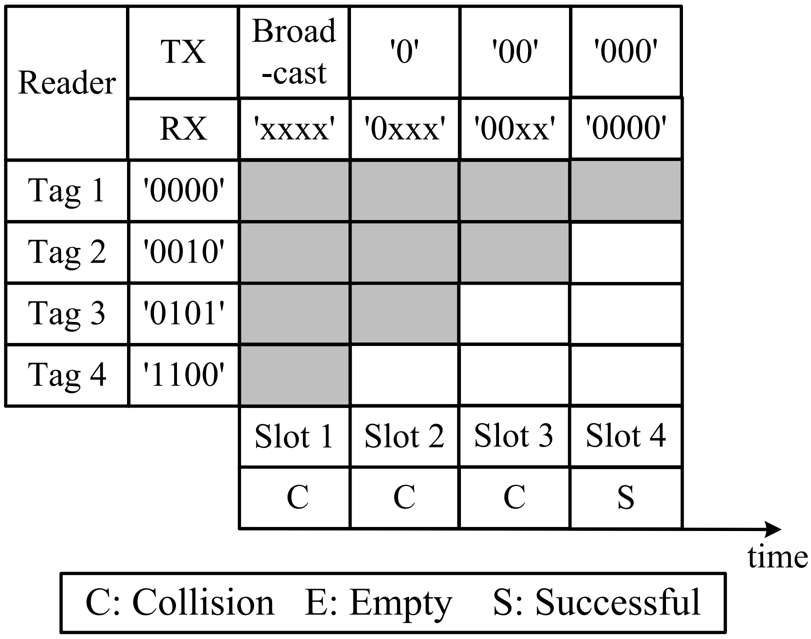


Figure 3.4: Query tree anti-collision algorithm example

signal asking them for a reply. A collision between the four tags is happening. The reader sends a '0' in a new query signal at time slot 2. However, there are three tags sharing this bit, so a new collision between the three tags is happening. Thereby, the reader has sent a '00' in its next query signal in time slot 3. At this time, there is a collision between two tags, leading the reader to send '000' in time slot 4. At last, the reader has received a single successful reply from tag 1. This process is repeated until the reader identify all the tags in the reading area.

3.2.2 Probabilistic Anti-collision Protocols

The main problem of using tree-based protocols is that these protocols are not efficient in dense networks (large number of tags), due to the increase in identification time [49]. Therefore, in dense network, ALOHA anti-collision protocols are more suitable. ALOHA anti-collision protocols are the most commonly used in UHF active and passive RFID. In these protocols, the readers do not know exactly the number of tags in the reading area to be identified. ALOHA anti-collision protocols are classified into the following four groups:

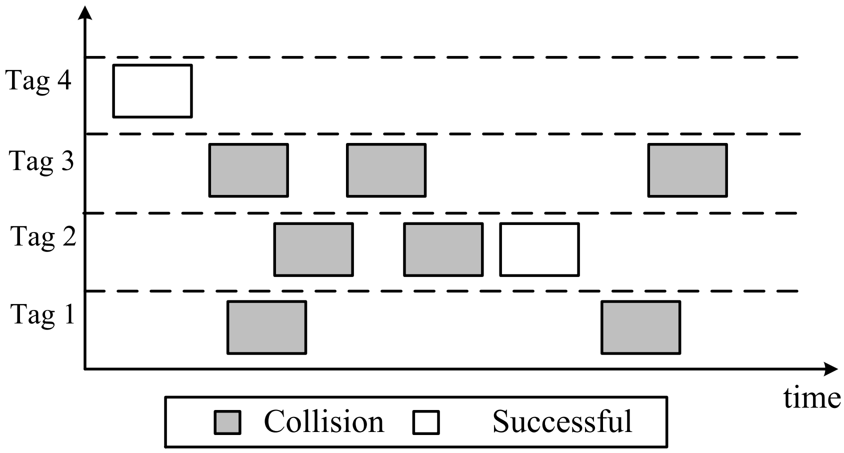


Figure 3.5: Example of pure ALOHA protocol

Basic ALOHA

The first group is widely known as basic ALOHA [50] anti-collision protocol. Basic ALOHA is the simplest anti-collision protocol for passive read-only-memory RFID tags. This protocol works as follows: The reader sends a query signal to power on tags. Then, tags send their ID randomly in time. The reader can only recognize the single tag reply case, without any ability to handle the collision. According to [50], the maximum reading efficiency is 18.4 %. Figure 3.5 shows an example of basic ALOHA for a single reader identifying four tags.

Slotted ALOHA

The second ALOHA anti-collision protocol is the slotted ALOHA (SA) protocol [51]. As shown in figure 3.6, slotted ALOHA is based on basic ALOHA. However, the time is divided into slots. In this protocol, the reader broadcasts a query signal which includes the beginning of each slot. Each tag chooses randomly if it will transmit in this slot or wait for a coming slot. The main advantage of this technique compared to basic ALOHA is: In slotted ALOHA, tag replies are completely synchronized. Therefore, collided slots overlap the tags timing completely. However, in the basic ALOHA protocol, the partial timing overlapping exists. Thus, the maximum reading efficiency using slotted ALOHA is 36.8 % [51].

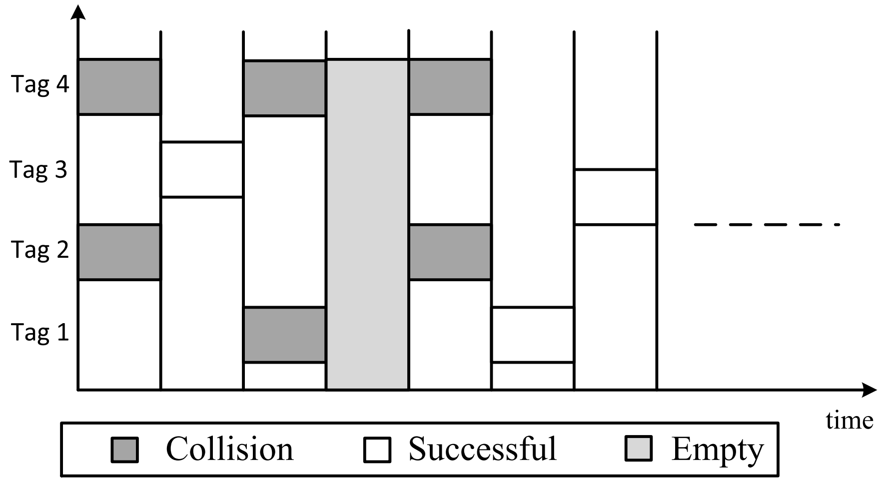


Figure 3.6: Example of slotted ALOHA

Framed Slotted ALOHA (FSA)

The third group is Framed Slotted ALOHA (FSA) [49]. The FSA anti-collision protocol uses a fixed frame length. Thus, the frame length is fixed during the complete tag identification process. At the beginning of each frame, the reader broadcasts a query signal to all tags. This signal includes the frame size. Each tag has to choose random number between 0 and $L-1$, where L is the frame length. If a collision happened, the colliding tags have to wait for the next frame.

Figure 3.7 presents an example for the identification process of four tags using FSA. In this example, the frame length is selected to four slots. According to figure 3.7, tag 4 transmits in the first slot alone. Thus, it is a successful slot. In the second slot, no tag has replied. So, it is an empty slot. In the third slot, tags 2 and 3 have replied together, which results in a collided slot. According to the FSA rules, tags 3 and 4 are not allowed to resubmit their IDs again during the same frame. Thus in slot 4, tag 1 only is allowed to reply to have another successful slot. In the next frame, the same procedure is repeated until all tags are identified.

Dynamic Frame Slotted ALOHA (DFSA)

The final type of ALOHA anti-collision protocols is Dynamic Framed Slotted ALOHA (DFSA) [52]. Using this algorithm, the number of slots per frame is

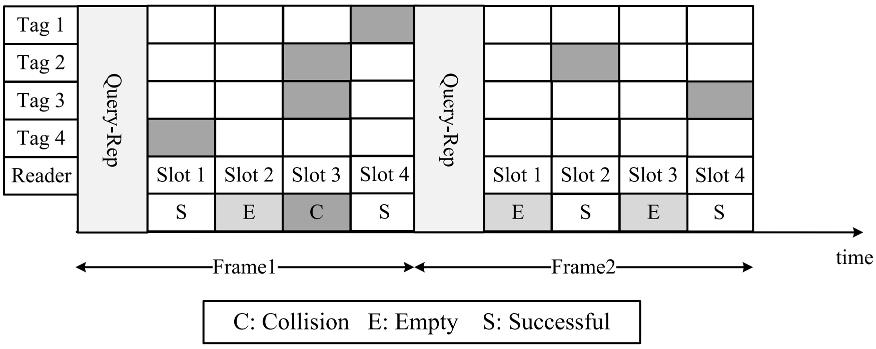


Figure 3.7: Example for Frame Slotted ALOHA

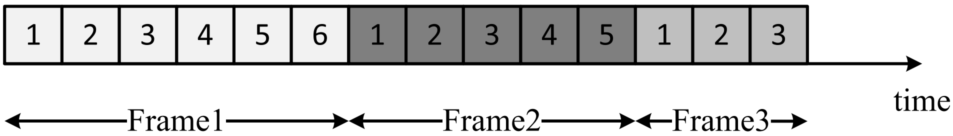


Figure 3.8: Slots of Dynamic Frame Slotted ALOHA

variable as shown in figure 3.8. According to the previously published RFID work, DFSA [53] is the most widely used anti-collision protocol for RFID systems owing to its simplicity and robustness. In DFSA, the reading process is divided into successive frames, in which each frame includes a specific number of slots. During the reading process, each active tag randomly assigns itself to one of the available slots in the frame. Therefore, each slot can take one of the following three variable states: 1) Successful Slot: One tag only chooses this slot, is fully identified, and then is deactivated by the reader within the successive frames. 2) Collided Slot: Multiple tags reply, resulting in a collision. The collided tags normally remain in their active state and retry their transmission in the next frame. 3) Empty Slot: No tag responds and the slot remains unused.

Increasing the reading speed can directly be translated into the maximization of the number of successful slots wrt. the number of idle or collided slots. Based on the Random Access Theory [54], for a given number of n tags, the expected number of empty E, successful S, and collided C slots in each frame with a length of L slots can be expressed by the following equations:

$$E = L\left(1 - \frac{1}{L}\right)^n, \; S = n\left(1 - \frac{1}{L}\right)^{n-1}, \; C = L - E - S \tag{3.1}$$

The conventional definition of the expected reading efficiency η_{conv} is given by the ratio between the expected number of successful slots S in a frame and the frame length L [55]:

$$\eta_{conv} = \frac{S}{L} \tag{3.2}$$

Based on (3.1) and (3.2), this results in the conventional definition of the efficiency:

$$\eta_{conv} = \frac{n}{L}\left(1 - \frac{1}{L}\right)^{n-1} \tag{3.3}$$

Figure 3.9 shows the FSA reading efficiency η_{conv} for a constant frame length $L = 64$ and different numbers of tags. The main goal of optimizing the DFSA algorithm is finding the optimal frame length L, which maximizes the reading efficiency η_{conv}. Based on (3.3), the reading efficiency η_{conv} is maximized when:

$$L_{opt} = n \tag{3.4}$$

In practical applications, the number of tags n in the interrogation region is unknown. Furthermore, the number of tags may even vary, e.g. when the tags are mounted on moving goods, because the successfully read tags get inactive in the following frames. Therefore, such applications employ DFSA [56]. First, DFSA has to estimate the number of tags in the interrogation area, and then has to calculate the optimal frame size L for the next reading frame. Figure 3.10 presents a summary for DFSA. As shown in the chart, the reader starts with an initial frame length. Then, it broadcasts this frame length to the tags in the reading area. Afterwards, it performs a normal FSA. At the end of the frame, the reader checks if there are any successful or collided slots. If yes, the reader estimates the remaining number of tags in the reading area, and then optimizes the next frame length and starts again normal FSA. If not, the reading cycle will be terminated.

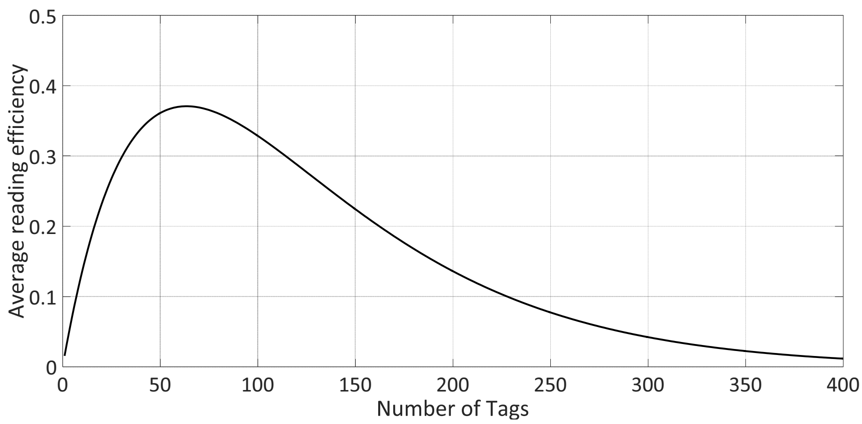


Figure 3.9: Frame Slotted ALOHA Reading efficiency, maximum reached for $L = n = 64$ tags of $\eta_{conv} = 0.36$

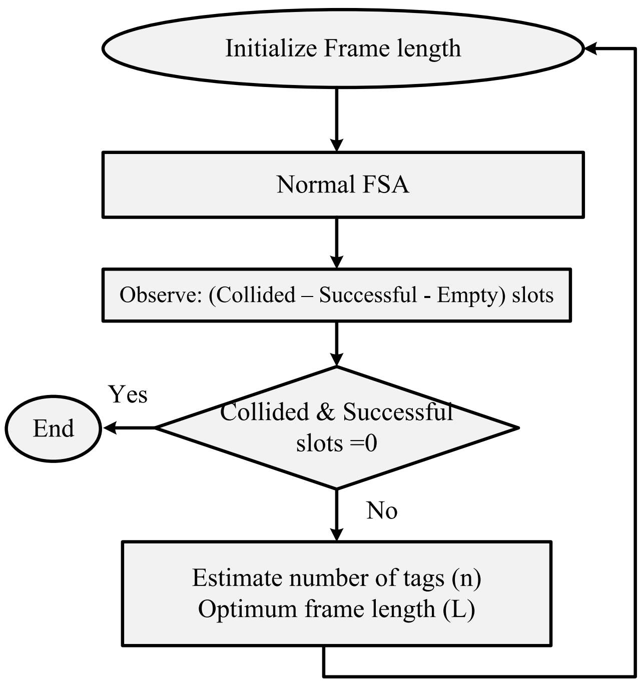


Figure 3.10: Flow chart of Dynamic Framed Slotted ALOHA (DFSA)

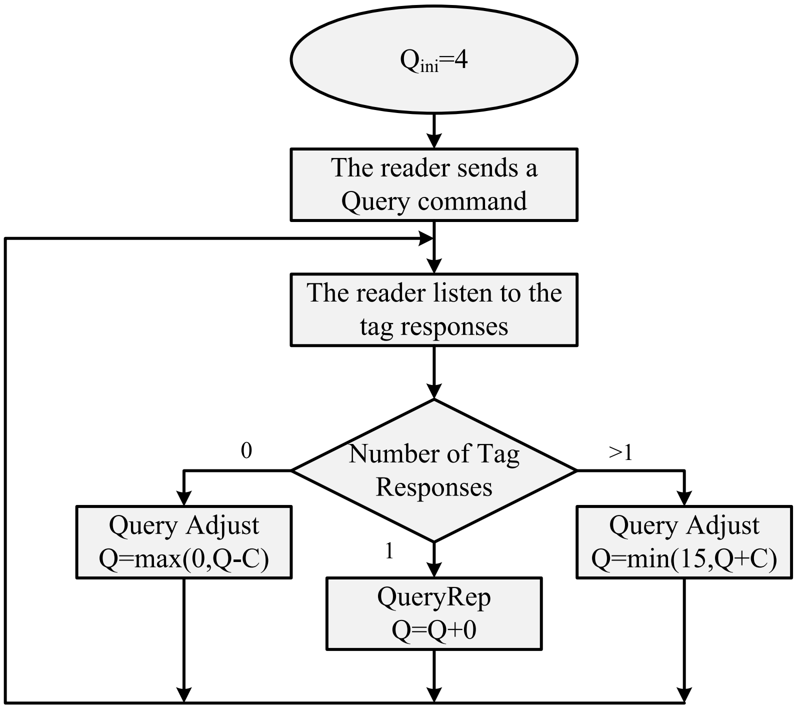


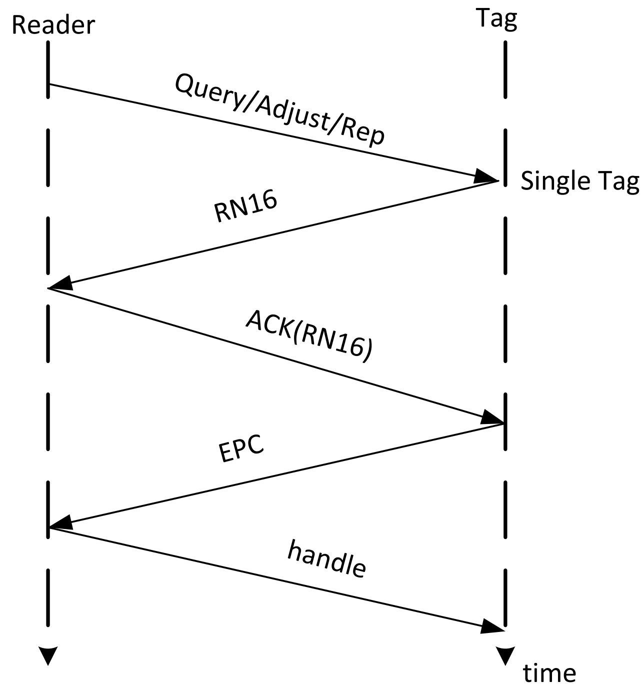
Figure 3.11: Conventional variable frame length procedure EPCglobal C1 G2 [11]

3.3 DFSA with EPCglobal C1G2

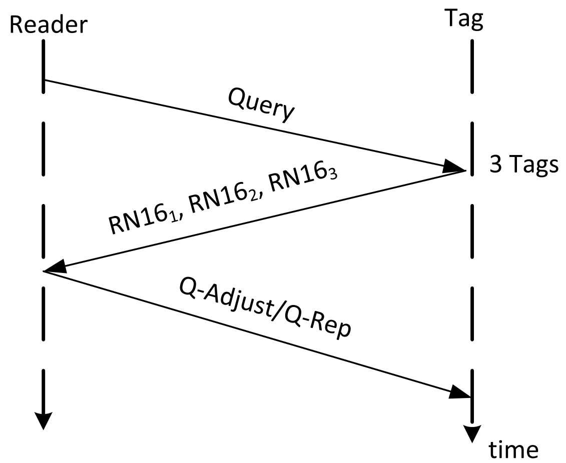
In this section, a brief introduction about DFSA with EPCglobal C1 G2 [11] will be given. The reading process consists of multiple inventory rounds. Each inventory round has a different frame length. Figure 3.11 shows an example for the frame length adaptation in EPCglobal C1 G2. According to figure 3.11, the initial frame length is $2^{Q_{ini}}$, where $Q_{ini} = 4$. Then each slot is checked. If there is no tag reply, the frame length should be decreased. If it is a collided slot, the frame length is increased. Finally, if the slot is a successful slot, the frame length will remain as it is.

Figure 3.12 shows an example for timing diagram of different inventory rounds between a single RFID reader and different tag reply situations. The reader starts with a "Query" command. In this command, the reader broadcast the current frame length for all the tags in the reading area. Each tag has to choose a random slot between 0 and $2^Q - 1$.

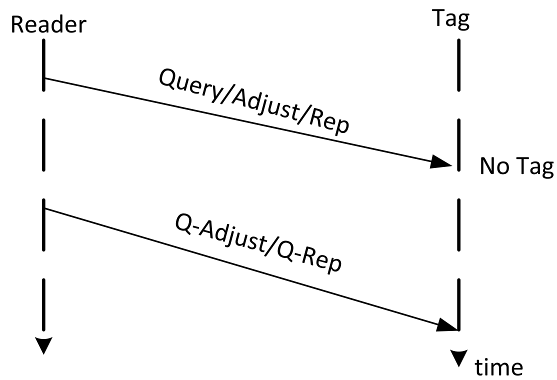
Figure 3.12a shows the case of single tag reply. In this case, the tag replies



(a) Single tag reply



(b) Multiple tags replies



(c) No tag reply

Figure 3.12: Example of an inventory between reader and different tags replies situations [11]

with its Random Number 16 (RN16), which is a 16 bits random number. When the reader receives this RN16 it will acknowledge this tag with an “ACK” command including this RN16. As soon as the tag receives a valid Acknowledgment (ACK) with its RN16, it will reply with its unique Electronic Product Code (EPC). Finally, the reader will send a “Handle” command to the tag to mute it until the end of the complete reading process. In figure 3.12b, the reader starts broadcasting a “Query” command for tags in the reading area. In the proposed example, three tags select this slot. Therefore, the reader receives simultaneously three different RN16s. In this case, the conventional RFID reader will not be able to decode any of these RN16s. The tags will wait for the next frame to be identified. Afterwards, the reader broadcasts a “Query-rep” command to inform all the remaining tags that the next slot will start. Figure 3.12c shows the behavior of an empty slot in EPCglobal C1 G2. The reader starts with a “Query” command, and waits for a tag reply during a certain time out period. If there is no tag reply during this time, the reader will terminate the slot by sending a new “Query-rep” command.

3.4 Cross Layer Anti-Collision Protocol

Recently, RFID receivers have been developed to be able to convert a part of collided slots into successful slots. Moreover, new RFID readers can even identify the type of the slots and terminate the empty and collided slots earlier. In this section, a brief discussion about these two parameters will be presented. Afterwards, a motivation to reconfigure the MAC layer to make use of the PHY-layer parameters is presented.

3.4.1 Collision Recovery in UHF RFID

Collision recovery in RFID systems is the capability of the reader to convert a part of the collided slots into successful slots. According to EPCglobal C1 G2, the reader can only acknowledge one single tag per slot. According to [57], the collision recovery capability of the RFID system depends on different factors: The capabilities of the receiver e.g. number of antennas, the distance between the collided tags, and the type of the channel.

Recently, some research groups (e.g. [58]) have concentrated on collision recovery using the spatial diversity of the received signal. They have proposed the following reading efficiency equation:

$$\eta = P(1) + \alpha \cdot \sum_{i=2}^{n} P(i), \tag{3.5}$$

where $\sum_{i=2}^{n} P(i)$ is the probability of collision, α is the average collision resolving probability coefficient. In this efficiency equation, the RFID reader can convert α part of the collided slots into successful slots. The authors have assumed unlimited and equal collision resolving probabilities coefficients. For example, the probability to resolve two collided tags is identical to the probability to resolve ten collided tags, which is a strong simplification. Another research groups [59–62] considered the limited capability of a RFID reader to resolve collisions. They have proposed a limited reading efficiency expressed as:

$$\eta = \sum_{i=1}^{M} P(i), \tag{3.6}$$

where $P(i) = \binom{n}{i}\left(\frac{1}{L}\right)^{i}\left(1-\frac{1}{L}\right)^{n-i}$, and M represents the number of collided tags that the reader is capable to recover. The authors assumed that the probability to recover one tag from i collided tags equals to 100%, independently of the actual i.

According to (3.5) and (3.6), the reading efficiency strongly depends on the capability of the physical layer to resolve the collision. Thus, in this thesis, the effect of the collision recovery capability on the MAC layer optimization will be addressed in more details.

3.4.2 Slots Durations in EPCglobal C1 G2

Conventional RFID systems cannot identify the type of the slots in FSA [56]. Therefore, such systems consider that the slot duration of FSA is constant, neglecting the type of the slot. Modern RFID readers can quickly identify the type of a slot (i.e. idle, successful, or collided). Hence, the durations of the different slot types are not identical, which reduces the overall reading time. Figure 3.13 shows two frames, each one with a frame length of $L = 6$ slots. The first frame in (a) presents the conventional view of the frame with equal slots

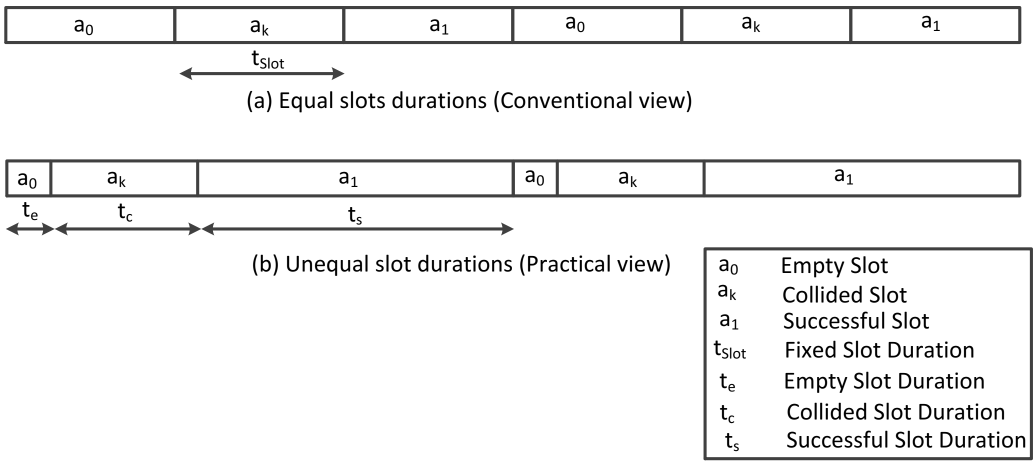


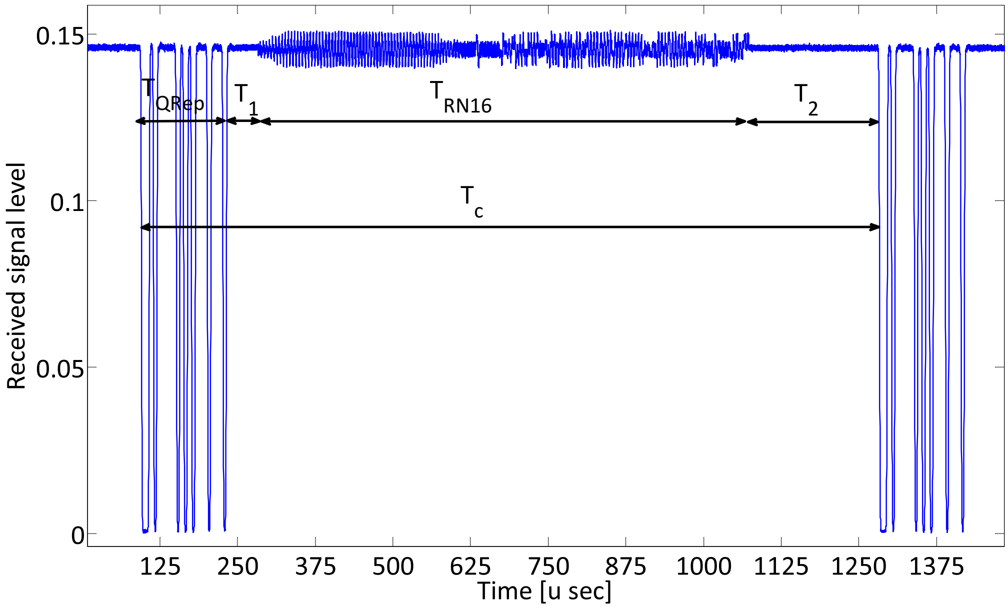
Figure 3.13: Equal and unequal views of slots in Frame Slotted ALOHA with frame length $L = 6$.

durations t_{Slot} for all slot types. The second frame in (b) presents the behavior of the real RFID slots behavior. Here, the slot duration depends on the slot type.

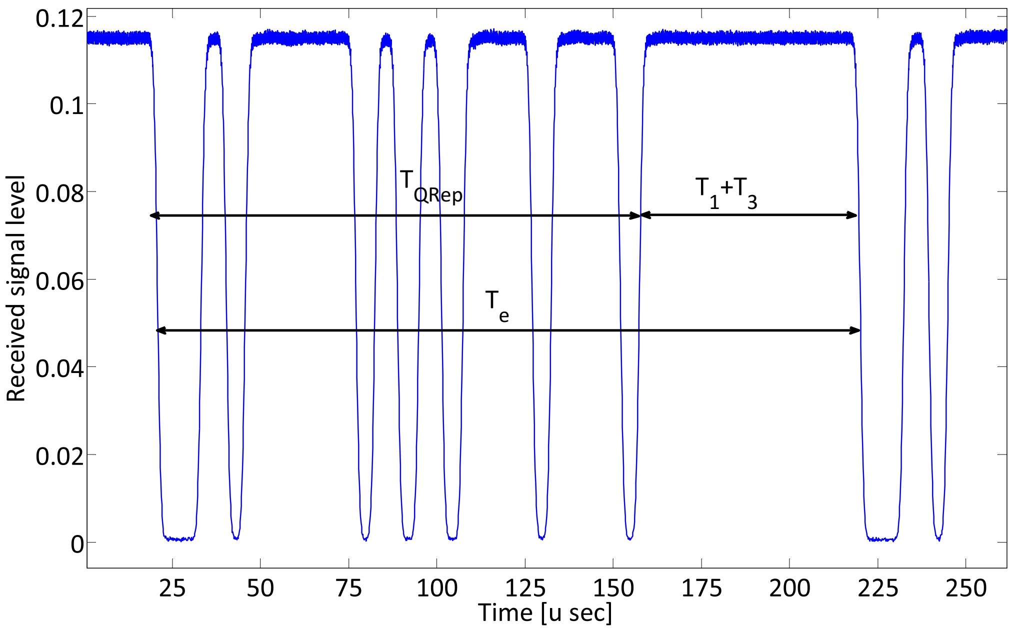
Figure 3.14 shows an example of real measurements for slots durations using the Universal Software Radio Peripheral SDR receiver (USRP B210) [63]. In these measurements, we used a sampling frequency of $f_s = 8\,\text{MHz}$, because the total RFID bandwidth in the European system is 4 MHz, the tags data rate is 160 kbps. For the given parameters and as shown in figure 3.14, the collided slot duration is $\simeq 1200\,\mu$sec, and the empty slot duration is $\simeq 200\,\mu$sec. Figure 3.14a shows a real collided slot between two tags. The number of Amplitude Shift Keying (ASK) levels in the RN16 is $A_L = 2^{N_c}$, where N_c is the number of collided tags. As shown in figure 3.14a, the number of ASK levels $A_L = 4$. In such a slot, the reader terminates the slot after recognizing that the slot is collided slot. Figure 3.14b shows that the reader terminates the slot directly when it recognizes that there is no tag reply in this slot.

According to the above discussion, the reading efficiency equation will be affected by the differences in slots duration, hence, the MAC layer optimization. In this thesis, the differences in slot duration length will be addressed in more details in the MAC layer optimization.

Summarizing, the main lack in the previous RFID research is that the MAC layer is optimized independently on the PHY layer. However, the PHY-layer



(a) Collided slot timing



(b) Empty slot timing

Figure 3.14: Slots durations measurements, $f_s = 8\,\mathrm{MHz}$, tag Backscatter Link Frequency $BLF = 160\,\mathrm{kbps}$

properties affect the optimization parameters of the MAC layer, e.g. the number of tags estimation and the optimum frame length. In this thesis, I will concentrate on optimizing the DFSA anti-collision protocol. In the proposed algorithm, the physical layer parameters will be considered, which are the physical collision recovery capability of the RFID reader and the differences in slot durations.

Chapter 4

Estimation of the Tag Population

In this chapter, the most common estimation algorithms following the EPC-global C1 G2 standard [11] are presented. Afterwards, a new number of tags estimation method called "Collision Recovery Aware Tag Estimation" will be introduced. The proposed method takes into consideration the collision recovery probability from the physical layer.

This chapter is organized as follows: Section 1 shows the conventional number of tags estimation algorithms with performance analysis comparisons between them. Section 2 presents the new collision recovery aware number of tags estimation method. Using this algorithm, a closed form solution for the estimated number of tags will be presented. The proposed solution presents a direct relation between the estimated number of tags and the frame length, successful and collided number of slots and the physical layer collision recovery probability.

4.1 State-of-the-Art Estimation Algorithms

The performance of the FSA algorithm strongly depends on the accuracy of the number of tags estimation and the frame size. For fast identification of RFID tags, an estimation of the number of RFID tags with the highest possible accuracy is the key issue for FSA based protocol. The number of tags estimation function calculates the number of tags based on feedback from the previous frame, which includes the number of slots filled with empty, successful, and collided slots. This information is then used by the function to obtain the number of tag estimate, and hence the optimal frame size L for a given round. According to the literature [53], the most common estimation algorithms are classified into four groups: heuristic Q-slot family, indirect heuristics Q-frame family, error minimization estimation, and Maximum Likelihood (ML) estimation.

4.1.1 Heuristics Q-slot Family

The EPCglobal C1 G2 standard [11] proposes an alternative frame length adaptation mechanism without any prior tag estimation. Using this mechanism, the initial frame length is fixed $Q_{ini} = 4$. Then, the frame length is adjusted slot by slot according to the slot type: empty, successful, or collided. The performance of this scheme strongly depends on the value of the variable C, where $C \in (0.1, 0.5)$. Since the value of C is not clearly defined in the standard, there are different proposals optimizing the value of C. c.f. Figure 3.11 shows the flow diagram of the heuristics Q-slot family.

Q^{+-}**Algorithm** This algorithm was proposed by [64]. Using this algorithm, the "Query" command is transmitted only if the reader has to calculate a new value of Q. Otherwise, the reader transmits the "QueryRep" command, because the "Query" command length is 22 bits and the "QueryRep" command length is only 4 bits. Moreover, the variable C is replaced by two variables: C_e and C_c.

C_e is used when an empty slot is detected by the reader, whereas, C_c is used when a collided slot is detected by the reader. The values of $C_e$and C_c are calculated numerically regardless of the number of tags in the reading area.

Optimum-C Algorithm: This algorithm was proposed by [65], where the optimum value of C is calculated numerically versus the previous value of Q. This is done by simulating a passive RFID system for the complete range of $Q \in [0, ..., 15]$ for each Q and $C \in [0.1, ..., 0.5]$ with step size 0.1. At last, the best combination is the one which gives the minimum identification delay.

Slot Count Selection (SCS) Algorithm: This algorithm was proposed by [66], in which the variable C is replaced by two variables C_1 and C_2 like using the Q^{+-} approach [64]. However, C_1 and C_2 for the SCS algorithm are calculated slot by slot as a function of other parameters. These parameters depend primarily on the Reader-to-Tags (R-T) and Tags-to-Reader (T-R) data rates. According to [66], the system performance will be improved if the values of C_2 and C_1 are set to be $C_2 \in [0.1, 1]$ and $C_1 = 0.1$, respectively. The authors neglected the effect of the modulation and the encoding scheme. According to [67,68], the correct value of (T-R) data rate strongly depends on the modulation and the encoding scheme.

According to [69], the heuristics Q-slot family is an, almost optimum anti-collision algorithm for small RFID networks, which have number of tags less than 50 tags. However, in a dense network, the performance of such algorithms is lowered.

4.1.2 Indirect Heuristics Q-frame Family

In dense RFID networks, the indirect heuristics Q-frame family gives better performance [69]. In this family, the proposed algorithms first calculate the estimated number of tags in the reading area $\hat{n}$. Then, it adjusts the optimum frame length L that maximizes the reading efficiency. The estimation process is based on information from the previous frame.

Lower Bound: This method was proposed by [56], taking a very trivial assumption for the lower bound of the number of tags in the reading area $\hat{n}$. It is not related to any theoretical lower bound. Additionally, it claims that each collided slot involves two collided tags. Therefore, it is presented as:

$$\hat{n}_i = S_i + 2 \cdot C_i \tag{4.1}$$

where i presents the frame index, S_i, and C_i successively present the number of successful and collided slots in frame i.

Schoute Algorithm: The Schoute algorithm [52] is based on the hypothesis that the frame length is equivalent to the number of unidentified tags $L = \hat{n}$

since this is a direct way to optimize the system throughput. Schoute's method also supposes that the number of unidentified tags $\hat{n}$ could be infinite. Let P_c be the probability that a slot is a collision slot and P_s be the probability that a slot is a successful slot. Then, the estimated collision rate C_{rate} is expressed as follows:

$$C_{rate} = \frac{P_c}{1 - Ps} \tag{4.2}$$

For dense RFID networks, $\hat{n}$ is a large number, the rate C_{rate} can be thus calculated as follows:

$$C_{rate} = \lim_{n \to \infty} \frac{P_c}{1 - Ps} \cong 0.418 \tag{4.3}$$

More details are discussed in [70].

Thus, the average number of tags involved in a collision slot C_{tag} is then computed as follows:

$$C_{tag} = \frac{1}{C_{rate}} \cong 2.39 \tag{4.4}$$

Therefore, Schoute's method estimates the number of estimated tags $\hat{n}$ as follows:

$$\hat{n}_i = S + 2.39 \cdot C_i \tag{4.5}$$

However, the supposed conditions in this method are too strict that some deviations would be generated if the real situation differs much from the strict conditions.

C-Ratio: The authors of the C-Ratio estimation method [71] proposed a binomial distribution for the number of tags. They assume the tags select a slot with probability of success $P = \frac{1}{L}$, where L is the frame length. The collision ratio is defined as the ratio between the number of collided slots C_i and the frame length L_i, where i is the frame index. Therefore, the C-Ratio can be expressed as:

$$C_{ratio} \triangleq \frac{C_i}{L_i} = 1 - \left(1 - \frac{1}{L_i}\right)^{n_i} - \left(1 + \frac{n_i}{L_i - 1}\right) \tag{4.6}$$

The optimum value of $\hat{n}_i$ is obtained by searching for all possible values of n, that makes the right hand side of (4.6) gives the closest value of C-Ratio, under the condition that $n_i \geq 2 \cdot C_i$.

In [72], the authors used the same concept as the C-Ratio. However, they presume independent binomial distributions of the tags in each slot. Thus, the modified C-Ratio is expressed as:

$$\frac{C_i}{L_i} = \sum_{j=2}^{n_i} \binom{n_i}{j} \left(\frac{1}{L_i}\right)^j \left(1 - \frac{1}{L_i}\right)^{n_i - 1} \tag{4.7}$$

To simplify the searching process, this estimator suggests applying an upper bound to estimate the number of tags.

4.1.3 Error Minimization Estimation

Vogt proposes an estimation algorithm based on the minimum squared error (MSE) estimation [54]. It minimizes the distance between the observed empty E, successful S, collided C slots and their expected values E_{exp}, S_{exp}, C_{exp} for a given frame length L. It is presented as:

$$\varepsilon_{conv}(L,\, S,\, C,\, E) = \min_{n} \{|E_{exp} - E| + |S_{exp} - S| + |C_{exp} - C|\} \tag{4.8}$$

where

$$E_{exp} = L_i \left(1 + \frac{1}{L_i}\right)^n, S_{exp} = n \left(1 + \frac{1}{L_i}\right)^{n-1}, C_{exp} = L_i - E_{exp} - S_{exp} \tag{4.9}$$

However, this method requires numerical searching to find the optimum value of the number of tags $\hat{n}$. Moreover, the author assumed that tags are identically distributed over slots, which is generally not a valid assumption.

4.1.4 Maximum Likelihood (ML) Tag Estimation

The main concept of ML number of tags estimation is to compute the conditional probability of observed events assuming that this conditional probability is function of the number of tags n. Subsequently, the $\hat{n}$ is the estimated number of tags which maximizes this conditional probability. In [73], the author proposes a ML number of tags estimation by finding the optimum $\hat{n}$ that gives exact E empty slots, S successful slots, and C collided slots, if there are L slots.

In addition, he uses a multi-nomial distribution with L repeated independent trials. Each trial has one of three possibilities: P_e empty, P_S successful, or P_c collision, where P_e , P_s , and P_c follow binomial distribution [56] and can be presented as:

$$P_e = \left(1 + \frac{1}{L}\right)^n, P_s = \frac{n}{L}\left(1 + \frac{1}{L}\right)^{n-1}, P_c = 1 - P_e - P_s \tag{4.10}$$

The probability that in L trails given E empty slots S successful slots, and C collided slots occur is:

$$P(\hat{n}|L, S, C, E) = \frac{L!}{E!S!C!} P_e^E P_s^S P_c^C, \tag{4.11}$$

This probability is the general term of the multi-nomial expansion of $(P_e + P_s + P_c)^L$. Therefore, for a read cycle with frame length L, a posterior probability for the number of tags n when E empty slots, S successful slots, and C collided slots are observed, is calculated as shown in (4.11).

4.1.5 Performance Comparison for Existing Estimation Protocols

According to literature [74–76], the most common comparison estimation performance metric is the relative estimation error ϵ versus the normalized number of tags n/L. It presents the absolute difference between the actual number of tags and the estimated one divided by the actual number of tags in the reading area. Accordingly, it is defined as:

$$\epsilon = \left|\frac{\hat{n} - n}{n}\right| \times 100\,\% \tag{4.12}$$

Figure 4.1 shows the comparison of the most common number of tags estimation algorithms used in the passive UHF RFID systems. The comparison metric is the average relative estimation error ϵ, which is calculated using Monte-Carlo simulations for FSA with 1000 iterations for each (n/L) value. According to figure 4.1, the simplest estimation algorithm presented is the lower bound Schoute algorithm [52]. It gives accurate results only when FSA frame length is equal to the number of tags $L = n$. The ML estimation method [73] is

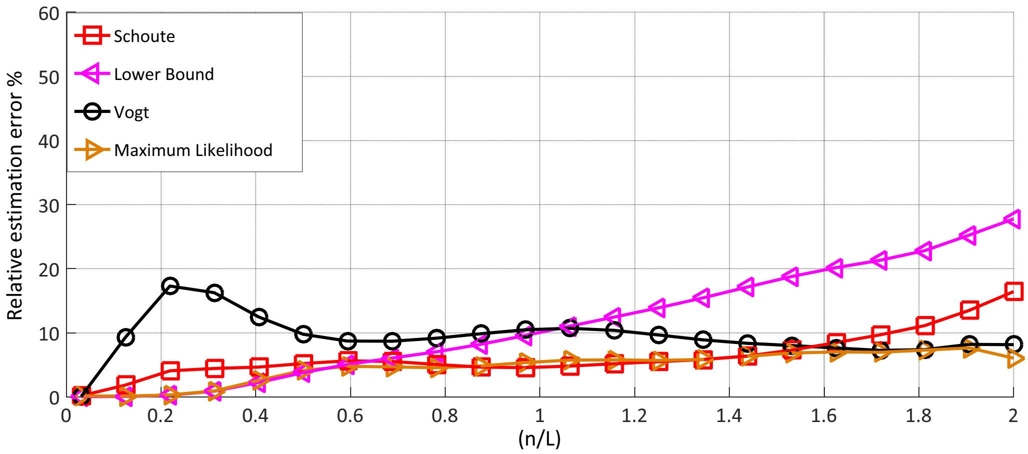


Figure 4.1: Relative estimation error ϵ vs. normalized number of tags $^n/_L$ for the common state-of the-art estimation algorithms

the most accurate estimation algorithm along the different values of L and n. It gives the minimum relative estimation error even in dense RFID networks, which is the main focus of the proposed work. However, according to [76], the complexity of the ML algorithm is much higher than the other estimation algorithm, because it searches for the value n that maximizes the estimation probability. This disadvantage makes ML estimation not a practical solution for dense RFID networks.

Figure 4.2 displays another comparison metric, which is the mean identification time required to identify n number of tags. The comparison is between the average identification time using FSA algorithm with the most common existing number of tags estimation protocols. According to figure 4.2, the ML estimation algorithm [73] results better results compared to the other estimation algorithms. However, the numerical searching complexity of the ML estimator [73] might lead to numerical instability problems for simple low-end devices as described in [53]. This leads us to search for a method compromising between the accuracy of the protocol and the stability of its implementation for dense RFID networks. Moreover, all these methods do not take into consideration the collision recovery capabilities effect of the modern RFID physical layer.

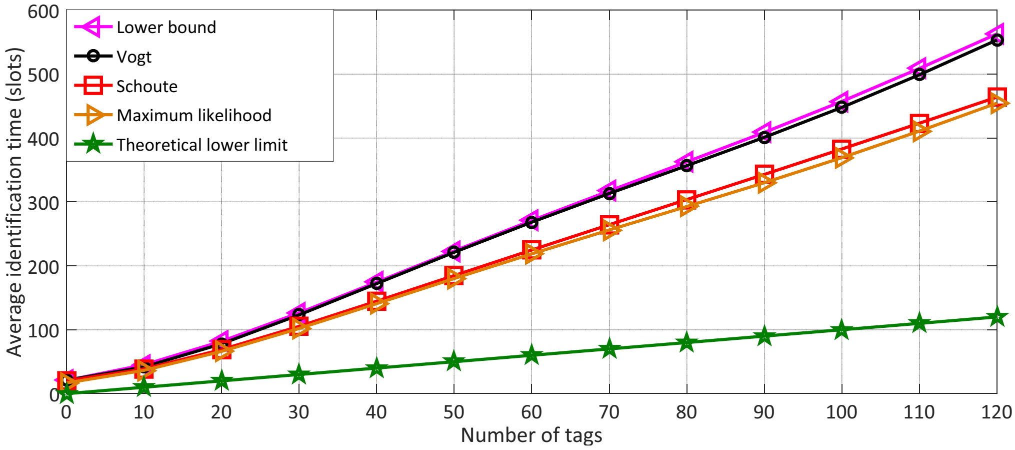


Figure 4.2: Mean identification time using FSA for simulated common state-of the-art estimation algorithms versus the number of tags in the reading area.

4.2 Novel Collision Recovery Aware Tag Estimation

The aforementioned literature proposed various estimation methods. The ML estimation method is the most precise results compared to other methods, however, it possesses two main disadvantages: 1) It uses numerical searching, which needs many calculations and iterations to find the optimum estimated value. 2) It neglects the physical layer effect, which is an inaccurate assumption. Modern systems are capable of converting part of collided slots into successful slots e.g. [60, 61]. In such systems, the number of collided and successful slots delivered to the MAC layer are inaccurate in regards to the real number of tags at the reading area. Therefore, it is important to take into consideration the collision recovery capability. Li [58] used the estimation approach of [54], hence, considering the collision recovery probability. However, this method leads to multi-dimensional searching, which needs a lot of iterations and complex calculations.

In this section, a new closed-form solution for the estimated number of tags $\hat{n}$ is proposed. It considers the collision recovery probability of the PHY layer. Then, an example for calculating the collision recovery probability using a simple RFID receiver will be presented. This solution gives a direct and linear relation between the estimated number of tags $\hat{n}$ and the frame length L.

4.2.1 System Model under Collision Recovery Probability

In this section, a new number of tags estimation method is presented. The proposed method is based on the classical ML estimation presented in [73]. According to the aforementioned method, the optimum value of $\hat{n}$ which maximizes the conditional probability of the observing vector $v = \langle C,\, S,\, E\rangle$ is used, given that n tags transmit at a frame length L:

$$P(\hat{n}|L, S, C, E) = \frac{L!}{E!S!C!} P_e^E P_s^S P_c^C, \tag{4.13}$$

where C, S, E are the number of collided, successful, and empty slots per a frame length L, successively, and P_e, P_s, P_c are the probabilities of empty, successful and collided transmissions per slot, respectively. Owing to the fact that modern RFID readers have a collision recovery capability, thereby, the physical layer converts part of collided slots into successful slots based on the following relation:

$$E = E_b,\; S = S_b + \alpha \cdot C_b,\; C = C_b - \alpha \cdot C_b, \tag{4.14}$$

where C_b, S_b, E_b are successively the expected number of collided, successful, and empty slots before the collision recovery of the system, and C, S, and E are respectively the expected number of collided, successful, and empty slots after collision recovery of the system, where α is a variable indicates the collision recovery capability of the physical layer. The calculation of the collision recovery probability will be discussed in details in the following sections. Figure 4.3 clarifies the flow diagram of the proposed system. In this system, the physical layer gives the MAC layer information about its collision recovery capability.

In the MAC layer, only the values of C, S, E are known after the PHY-layer collision recovery. In this stage, there is no information about these values before the collision recovery. Thus, the conventional estimation systems, including the classical ML number of tags estimation in (4.13) use the values of C, S, E after collision recovery in their calculations. However, these values are not accurate indicators for the actual number of tags in the reading area. In the proposed solution, the value of the current average collision recovery probability

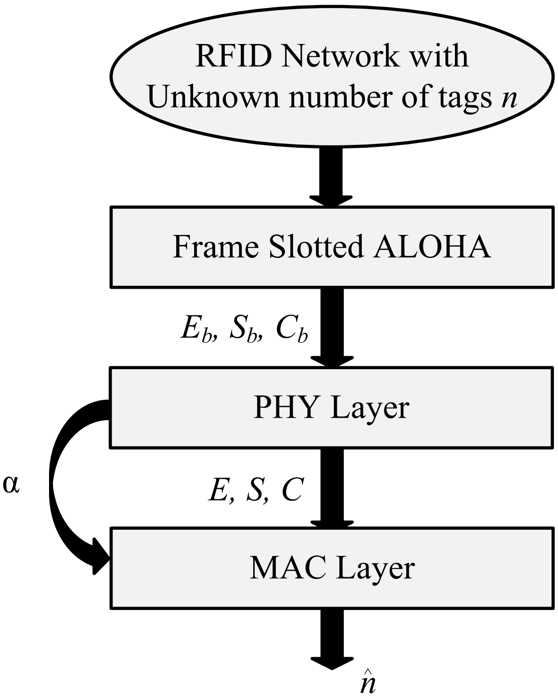


Figure 4.3: Physical layer collision recovery capability

α is estimated, as it will be shown in details in the following section. Finally, the expected corresponding values of C_b, S_b, E_b are calculated as:

$$E_b = E,\, C_b = \left\lfloor \frac{C}{1-\alpha} \right\rfloor,\, S_b = S - \left\lceil \frac{\alpha}{1-\alpha} \right\rceil C \tag{4.15}$$

Under the condition:

$$L = E_b + S_b + C_b \tag{4.16}$$

Thus, $C_{b(max)} = L - E_b$ and $S_{b(min)} = 0$. Therefore, the proposed collision recovery aware ML conditional probability can be formalized as:

$$P(\hat{n}|L, S, C, E, \alpha) = \frac{L!}{E_b!S_b!C_b!} P_e^{E_b} P_s^{S_b} P_c^{C_b} \tag{4.17}$$

According to [77, 78], for those situations in which n is large and $\frac{1}{L}$ is very small, the Poisson distribution can be used to approximate the binomial distribution. Figure 4.4 shows the success probability using Binomial distribution and its Poisson approximation versus the number of tags with different frame lengths. According to figure 4.4, the larger the number of tags n and the longer

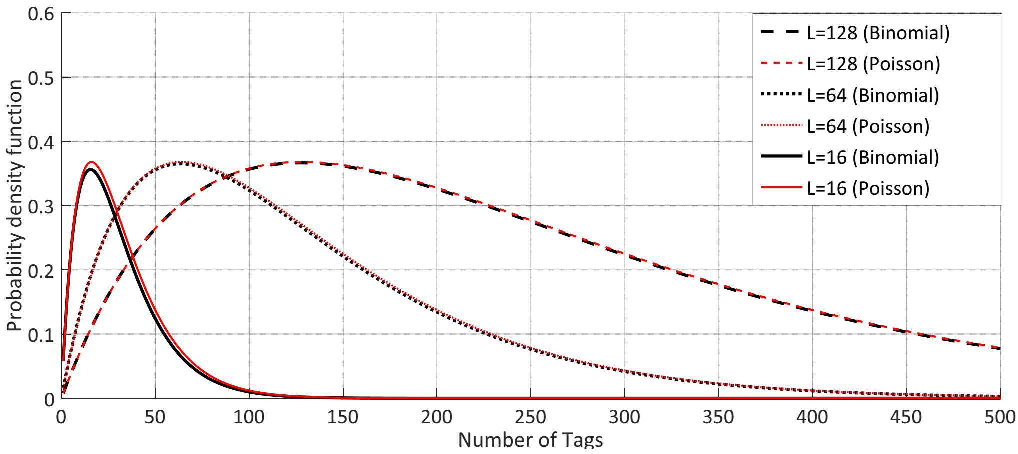


Figure 4.4: Binomial distribution and its Poisson approximation for probability of success using different frame lengths

the frame length L, the better the approximation. Based on figure 4.4, this approximation is valid under conditions $n \geq 10$ and $L \geq 16$.

This thesis focuses on dense RFID networks. So, the use of the suggested approximation in [53] for the tag probability of transmission per slot, which is considered as independent Poisson random variables with unknown mean $\gamma = \frac{\hat{n}}{L}$, is applicable. Thus, the probability functions can be presented as follows:

$$P_e = e^{-\gamma},\ P_s = \gamma \cdot e^{-\gamma},\ P_c = 1 - e^{-\gamma} - \gamma \cdot e^{-\gamma} \tag{4.18}$$

After substituting by (4.18) in (4.17) the proposed conditional probability is:

$$P(\hat{n}|L, S, C, E, \alpha) = \left(\frac{L!}{E_b!S_b!C_b!}\right) \gamma^{S_b} \cdot e^{-\gamma \cdot L} \cdot \left(e^{-\gamma} - 1 - \gamma\right)^{C_b} \tag{4.19}$$

The term of $\frac{L!}{E_b!S_b!C_b!}$ is not a function of the number of tags. It is only an offset and can be normalized. Thus, the proposed normalized conditional probability is:

$$P(\hat{n}|L, S, C, E, \alpha) = \gamma^{S_b} \cdot e^{-\gamma \cdot L} \cdot \left(e^{-\gamma} - 1 - \gamma\right)^{C_b} \tag{4.20}$$

Equation (4.20) gives a conditional probability for the estimated number of tags for a given number of successful, collided, empty slots and collision recovery probability. The computation of (4.20) can be done by numerical searching to obtain the optimum value of $\hat{n}$ which maximizes (4.20). Hence, the calculation of (4.20) leads to a multi-dimensional lookup table, which is time consuming, especially in case of dense network containing large number of tags n.

4.2.2 Derivation of the Proposed Closed Form Solution

This section will propose a closed form solution for the collision recovery aware estimation. This is achieved by differentiating (4.20) with respect to γ and equating the results to zero. After differentiating, the equation can be simplified as:

$$e^{-\gamma}\left(1+\frac{\gamma\left(\gamma\cdot L-S_b\right)}{\left(\gamma\cdot L-S_b-\gamma\cdot C_b\right)}\right)-1=0 \tag{4.21}$$

The analysis of (4.21) indicates that the relevant values for γ are in the region close to one [79]. Hence, we can develop a Taylor series for $e^{-\gamma}$ around one which leads to:

$$e^{-\gamma}\simeq 1-\gamma+\frac{1}{2}\gamma^2-\frac{1}{6}\gamma^3. \tag{4.22}$$

After substituting (4.21) and some additional simplifications, the final equation is a fourth order polynomial:

$$\begin{aligned}\underbrace{\frac{1}{120}\left(L-C_b\right)\gamma^4}_{(a)}+\underbrace{\frac{1}{24}\left(L-C_b-\frac{S_b}{5}\right)}_{(b)}\gamma^3+\underbrace{\frac{1}{6}\left(L-C_b-\frac{S_b}{4}\right)}_{(c)}\gamma^2\\ \underbrace{+\frac{1}{2}\left(L-C_b-\frac{S_b}{3}\right)}_{(d)}\gamma-\underbrace{\left(C_b+\frac{S_b}{2}\right)}_{(e)}=0\end{aligned} \tag{4.23}$$

Equation (4.23) has four roots [80]:

$$\begin{aligned}\gamma_{1,2} &= -\frac{b}{4a}-S\pm 0.5\sqrt{\underbrace{-4S^2-2P+\frac{q}{S}}_{X}} \\ \gamma_{3,4} &= -\frac{b}{4a}+S\pm 0.5\sqrt{\underbrace{-4S^2-2P-\frac{q}{S}}_{Y}},\end{aligned} \tag{4.24}$$

where $P = \frac{8ac-3b^2}{8a^2}$, $q = \frac{b^3-4abc+8a^2d}{8a^3}$

and, $S = 0.5\sqrt{-\frac{2}{3}P + \frac{1}{3a}\left(Q + \frac{\triangle_0}{Q}\right)}$, $Q = \sqrt[3]{\frac{\triangle_1+\sqrt{\triangle_1^2-4\triangle_0^3}}{2}}$.

with, $\triangle_0 = c^2 - 3bd + 12ae$, $\triangle_1 = 2c^3 - 9bcd + 27ad^2 - 72ace$

According to equation (4.16), the signs of the polynomial coefficients are constant and have the following signs: $a > 0$, $b > 0$, $c > 0$, $d > 0$, and $e < 0$.

Using Descartes' rules of sign [80], the number of real positive solutions of a polynomial can be counted. Assuming that the polynomial in (4.23) is $P(\gamma)$, and let ν be the number of variations in the sign of the coefficients a, b, c, d, e, so $\nu = 1$. Let n_p be the number of real positive solutions. According to Descartes' rules of sign [80]:

- $n_p \leq \nu$ which means that $n_p = 0 \,\text{or}\, 1$.
- $\nu - n_p$ must be an even integer. Therefore, $n_p = 1$.

Hence, there is only one valid real positive solution for the equation. Hereby, the valid solution will be identified. There are two possibilities for the solutions:

1. One positive real solution and the remaining three solutions are negative. In this case, all solutions are real and we just need to identify the root with the largest values among the four solutions. According to (4.24), the value of the square roots $\sqrt{X}$ and $\sqrt{Y}$ are positive reals, because we do not have complex solutions. This means, $\gamma_1 > \gamma_2$ and also $\gamma_3 > \gamma_4$. So, the solution will be either γ_1 or γ_3. Moreover, the value of S should be also a positive real, and q has always negative real value. So $\gamma_3 > \gamma_1$ which means in this case that our solution is γ_3.

2. Two complex solutions, one real positive solution, and one negative solution. In this case, we have either $\gamma_{1,2}$ or $\gamma_{3,4}$ real solutions. S should be a positive real number, and the complex value comes only from the square roots $\sqrt{X}$ and $\sqrt{Y}$. Moreover, q has always negative real value. Therefore, in (4.24) the value of $X < Y$. So $\gamma_{1,2}$ must be the complex roots, and as mentioned before that $\gamma_3 > \gamma_4$, so γ_4 is the negative root and γ_3 is the positive real root.

Based on the above discussion, the proposed closed form solution for the collision recovery aware tag estimation is:

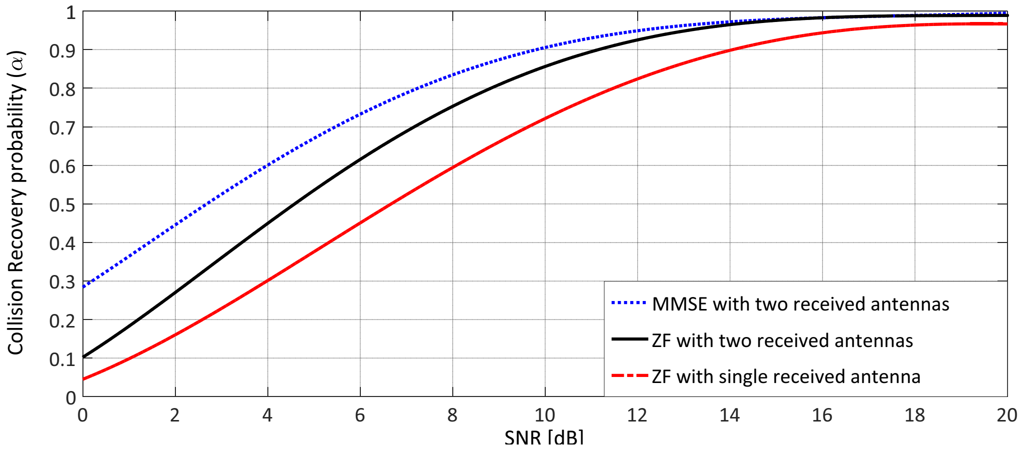


Figure 4.5: Collision recovery probability versus the signal to noise ratio

$$\hat{n} = \left(-\frac{b}{4a} + S + 0.5\sqrt{-4S^2 - 2P - \frac{q}{S}}\right) \cdot L \tag{4.25}$$

Equation (4.25) gives a direct and linear relation between the estimated number of tags $\hat{n}$ and the current frame length L, and gives an alternative solution to the numerical searching with (4.20). Thus, using (4.25), with neither look-up tables nor searching, reduces the complexity and the processing time of the estimation algorithm, is needed.

4.2.3 Collision Recovery Probability Calculation

The collision recovery capability is the ability of the reader to actively convert collided slots into successful slots. This capability does not only exist in the modern RFID readers but also in the simple readers, when the tags are well separated. Thus, the received signal power of the near tag will be much stronger than the received signal power from the far tag. Therefore, this ability is a function of two main parameters: First, the characterization of the RFID reader e.g. (receiver type, number of antennas, etc.). Second, the function of the current Signal-to-Noise Ratio (SNR). Therefore, it extends the capture probability, which is mainly an effect of the channel, resulting in a significantly higher probability to recover collided slots.

Figure 4.5 shows three receivers proposed by [81]. These three receivers are: 1) the Minimum Mean-Square Error (MMSE) receiver, 2) the Zero Forcing(ZF)

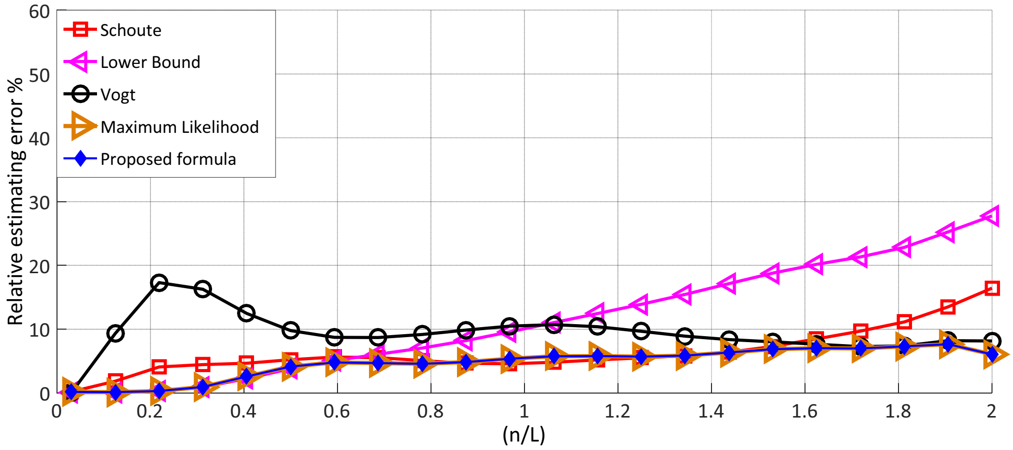


Figure 4.6: Relative estimation error with system has no collision recovery capability ($\alpha = 0$)

receiver with two receiver antennas, and 3) the ZF receiver with a single receiver antenna. The authors of [81] presented Bit Error Rate (BER) curves for the different receiver types as a function of the SNR. Thus, the BER can be mapped to a Packet Error Rate (PER) by means of simulations using the same methodology presented in [79]. Afterwards, the collision recovery probability is calculated as: $\alpha = (1 - PER)$. Figure 4.5 shows the values of the capture probabilities versus the average signal to noise ratio per frame. In this thesis, the average capture probability is calculated from the corresponding average SNR at the current frame.

According to figure 4.5, the higher SNR at the receiver, the higher the collision recovery capability of the reader. Figure 4.5 shows two different receivers ZF and MMSE. The MMSE receiver gives better performance than the ZF receiver, and the performance increases when we increase the number of received antennas. According to the practical measurements, the practical SNR range for the successful slots is between 4 dB and 12 dB [79].

4.2.4 Performance Analysis

In this section, the performance comparison between the proposed collision recovery aware number of tags estimation and the most common estimation algorithms in the state-of-the-art will be presented. The relative estimation error will be used as a comparison metric, as it is the most common comparison

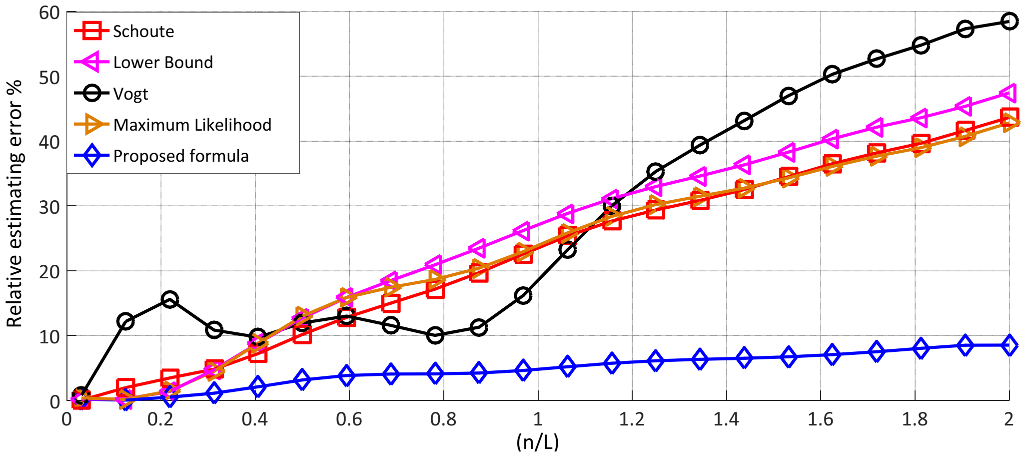


Figure 4.7: Relative estimation error with system has collision recovery capability ($\alpha = 0.7$)

metric for estimation algorithms.

Figure 4.6 shows the percentage of the relative estimation error for the proposed system compared to the literature. These simulations use system that has no collision recovery capability ($\alpha = 0$). According to figure 4.6, when the number of tags compared to the frame length increases, the relative estimation error increases. This is due to the increase of the number of collided slots per frame. As shown in figure 4.6, the proposed system gives identical relative estimation error compared to the classical ML estimation algorithm [73]. Moreover, the proposed system gives a closed form solution of [73]. This advantage decreases the complexity of the estimation algorithm.

Figure 4.7 demonstrates the influence of the collision recovery capability on the proposed estimation protocol compared to other estimation protocols. In this simulations, the MMSE RFID reader which is proposed in [82] is used. These simulations use an average SNR=6 dB . According to figure 4.5, the corresponding collision recovery probability $\alpha = 0.7$. According to figure 4.7, the proposed solution has a more accurate estimation performance compared to the existing methods in the state-of-the-art.

Figure 4.8 shows the relative estimation error versus the full range of the collision recovery probability $0 \le \alpha \le 1$. In this simulation, the number of tags in the reading area is equal to the frame length i.e. $n = L$, which is the optimum case for the conventional FSA. Based on figure 4.8, when the value of

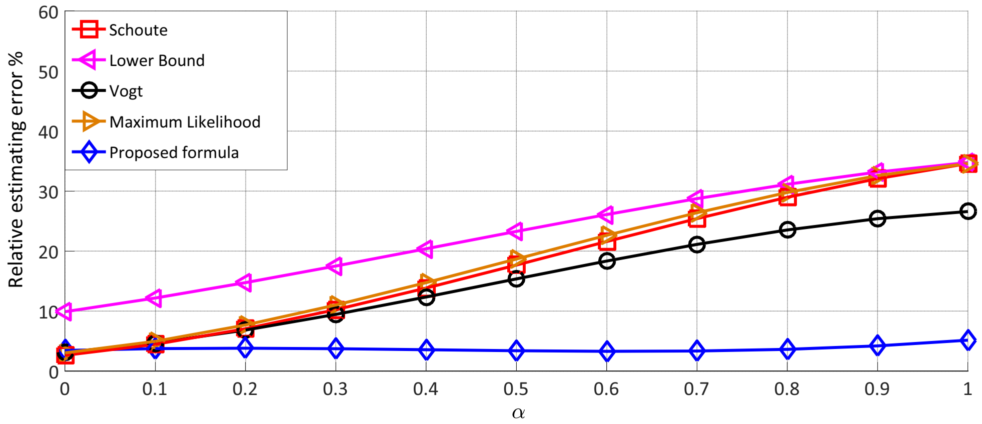


Figure 4.8: Relative estimation error vs. collision recovery probability α , where $L = n$

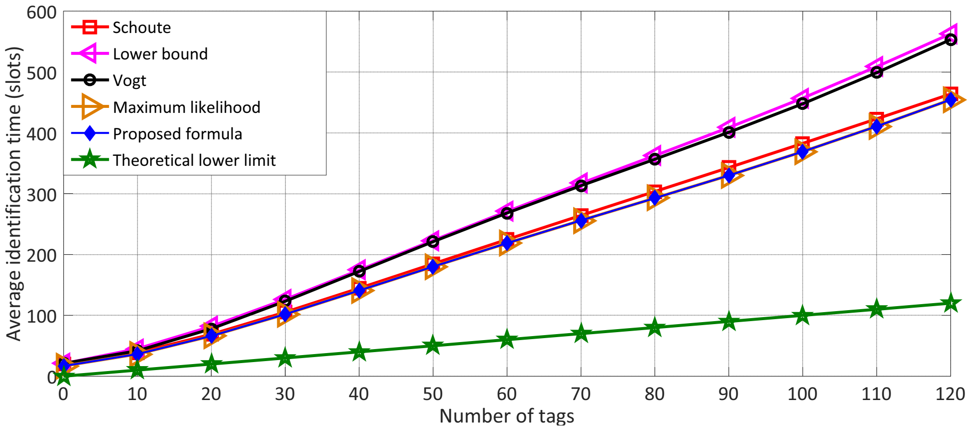


Figure 4.9: Average identification time system has no collision recovery capability ($\alpha = 0$)

the collision recovery probability increases, the relative estimation error of all estimation algorithms increases, except for the proposed estimation protocol that has almost constant performance, independent of the value of the collision recovery probability. The proposed method takes into account the collision recovery probability, which is produced by the PHY-layer. According to figure 4.8, the relative estimation error of the proposed algorithm is 4 %, which verifies the results of figure 4.6 at $\frac{n}{L} = 1$ and verifies the simulation results of figure 4.7 at $\frac{n}{L} = 1$.

In dense RFID applications, the average identification delay (time) is the most important performance metric. Thus, figure 4.9 displays the average iden-

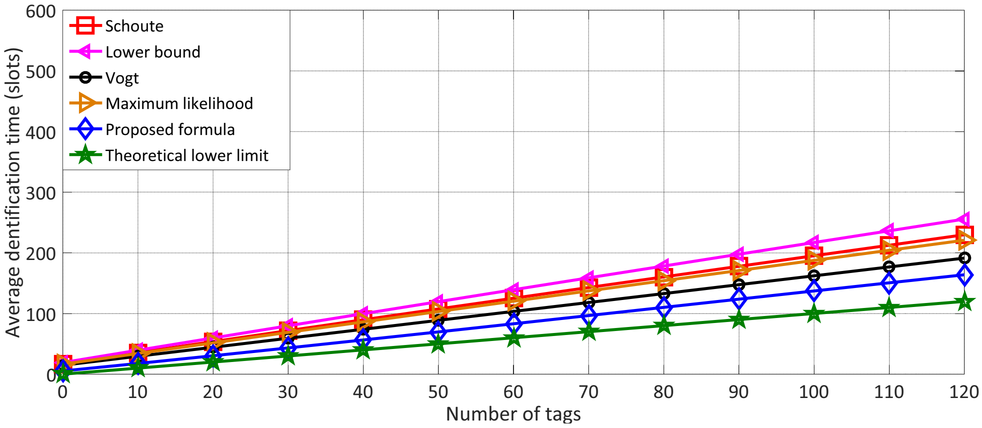


Figure 4.10: Average identification time system has collision recovery capability ($\alpha = 0.7$)

tification delay for a number of tags. In these simulations, FSA is applied with an initial frame length of $L_{ini} = 16$, which is the conventional initial frame length used in EPCglobal standard [11] is used. Figure 4.9 shows the identification time for systems with no collision recovery capability ($\alpha = 0$). According to 4.9, the proposed system assigns identical results compared to [73] and better results than the other systems in the literature. Figure 4.10 shows the average identification delay for systems exhibiting a collision recovery probability $\alpha = 0.7$. According to figure 4.10, the average identification delay has decreased for all the systems due to the collision recovery capability. The proposed system gives better results compared to the state-of-art due to the performance of estimation only.

According to EPCglobal C1 G2, the RFID reader cannot acknowledge more than single tag per slot. Therefore, the theoretical lower limit to identify n tags is n slots. According to figure 4.10, there is still room of improvement between the proposed algorithm and the theoretical lower limit with $\simeq 30\,\%$. Therefore, in the following chapter, new proposals regarding the FSA frame length taking into consideration the PHY-layer properties will be presented.

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