RFID Multiple Access Methods

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Abstract - Due to their limitless possibilities and low cost, RFID systems are powerful object identification tools well-suited in everyday applications. When attempting to identify multiple RFID tags from densely populated fields within the shortest timeframe possible, the typical design characteristics of RFID systems lead to a problematic lack of adequate resources to efficiently do so. After a brief introduction to RFID we present several forms of the multiple-access protocol Aloha known from networking to resolve collisions, with special focus on the variants thereof which make them attractive for deploying in RFID systems. We then review a series of commercially available or standards-defined RFID systems, and liken the contention resolution protocols used to the presented Aloha variants. The problematic of comparing the systems' performance will be addressed, and several systems briefly put against one-another.

1 Introduction

RFID systems are composed of three main components:

- one or more RFID tags, also known as transponders (transmitter/responder), are attached to the objects to count or identify. The most common form of tag receives its power from the interrogation signal, consisting mainly of a microchip and coiled antenna, with the main purpose of storing data;
- a reader, or transceiver (transmitter/receiver) made up of an RF module and control unit, which sends the interrogation signal to the tags;
- a Data Processing Subsystem, which can be an application or database, depending on the application.

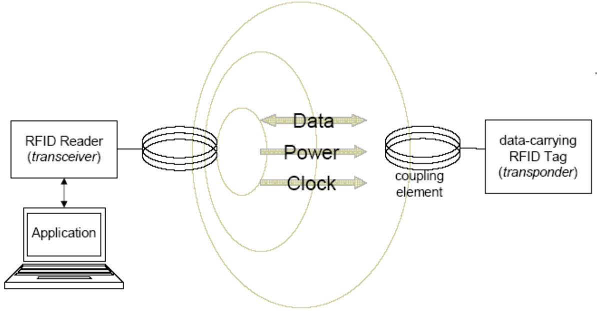

Figure 1: RFID system architecture

The ability to reliably identify multiple tags within the shortest timeframe possible is an important factor to everyday applications, and is severely limited due to RFID tag design requirements.

Most assumptions made in classical networking before deriving algorithms for multiple access to a common medium cannot be similarly made in RFID systems.

- The first limiting factor for RFID systems is the constraint on memory and computation capabilities, to account for the low manufacturing costs. The tags are consequently limited to very simple calculations.
- Secondly, several regulatory bodies[1] restrict the readers' maximum operating field strength negatively affecting the number of possible Reader-to-Tag transmissions, thus driving the need to minimize reader to tag messages
  - ex.: ISO18000-Part3 (MODE1) which describes 13,56MHz air interface communications,
    6,6kbps tag -> reader >> 1,65kbps reader -> tag [iso18000-3]
- The most important and determining factor however, is the inability to sense the medium preventing tags to be aware of each others' presence and transmissions. This common assumption is of crucial importance, since most (if not all) collision resolution algorithms first need a means to determine when a collision occurs as a starting point.

For the above enumerated limitations as well as many others, RFID systems are special cases of the multiple channel access communication problem. Many standard collision-resolution protocols are for this reason non-applicable or difficult to implement in RFID systems.

The next section focuses on three variants of the collision resolution protocol Aloha borrowed from classical networking, and describes extensions suggested to make them more applicable to RFID systems. Section 3 presents examples of commercial RFID systems existing on the market, chosen for their methods to resolve collisions. Section 4 attempts to compare the systems on the basis of their implemented methods for collision resolution, subsequently questioning the eligibility of such a comparison. The final section deals with the related collision avoidance methods and summarizes the collision resolution methods and implementations reviewed.

2 Aloha and Collision Resolution

2.1 (Pure) Aloha

The Aloha protocol is a very simple time-division multiple access (TDMA) protocol: a tag begins transmitting as soon as it is ready and has data to send.

The implicit start of the exchange between the tags and a reader, with the tags automatically sending their IDs upon entering a powering field, is one of the most basic properties observed in Aloha protocols. This is referred to as a "Tag-Talks-First" behaviour, the opposite of which would be a "Reader-Talk-First" behaviour, as is seen in several, if not most, implementations.

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[1] US: FCC
EU: EN
Japan: ARIB

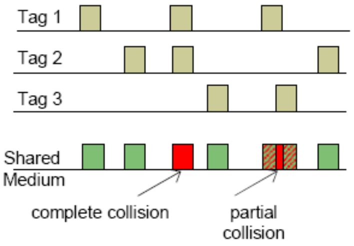

Figure 2: (pure) Aloha example

If by misfortune some other tag has data to send around that time (whether earlier or later) and the interval during which the two tags transmit overlaps, then a complete or partial collision occurs.

As the simplest form of a random backoff protocol, a collision forces the tag cease transmitting, only to retransmit after a randomly determined delay.

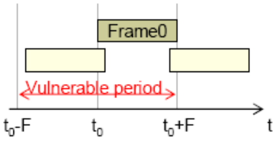

Figure 3: Aloha frame vulnerability

The problem that arises with the use of the Aloha protocol is the time period during which a frame F is vulnerable to a collision. Due to the continuity on the time axis, any tag that begins transmitting in the period $t_0 - F$ to $t_0 + F$ will cause at least a partial collision.

The second difficulty particular to RFID systems, is the inablility to detect or sense the carrier, as is assumed for classical networking. As a functionally equivalent workaround, the collision (or lack thereof) is determined at the tag by listening for the reader's (N)ACK, or otherwise simply goes undetected.

Such problems make implementing the Aloha protocol in its simplest form somewhat unsuited to RFID systems, and several extensions have been proposed in [EMMicro98, iso18000-3] in order to increase Aloha's feasibility and efficiency.

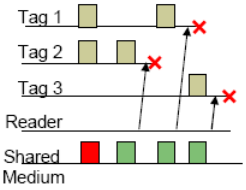

Figure 4: "Switch-off"

The first technique is named **"Switch-off"**, under which successfully decoded tag responses result in the tag automatically entering a `Quiet` state where it no longer transmits its ID to the reader. This will be further explained in the next section relating to Slotted-Aloha protocols.

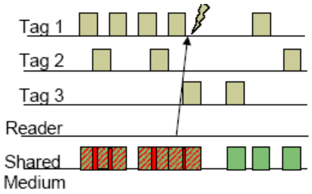

Figure 5: "Slow-down"

The second method called **"Slow-down"** is a compromise between pure Aloha and the "Switch-off" extension, whose goal is to diminish tags' reply frequencies. This is accomplished by the reader sending a certain tag a `slow-down` command when it feels overwhelmed by responses from this particular tag. The singled-out tag then adapts the randomness of its backoff algorithm, such that the rate at which it transmits its ID is reduced.

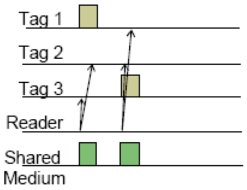

Figure 6: "Carrier Sense"

The third method **"Carrier Sense"** is meant as a way to confer to the tags a means of listening to the medium and determine if a transmission is currently in progress. This is described exclusively in [EMMicro98], whereby the reader uses its capacity to listen to the medium in order to convey extra information to the tags. A special `MUTE` command is broadcast to the remaining tags in the reader's field as early as possible after a transmission is detected, while still making sure it is a transmission and not just noise. The earlier a `MUTE` is sent, in effect silencing tags for the (predetermined) length of an ID transmission, the smaller the probability that another transponder has started a colliding transmission.

2.2 Slotted-Aloha

The Slotted-Aloha protocol is obtained by the addition of a constraint to pure Aloha: time is divided into discrete time intervals, called slots.

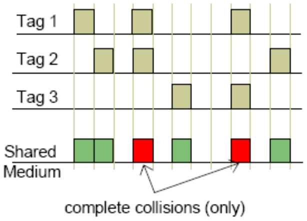

Figure 7: Slotted-Aloha example

A tag is then constrained to begin transmitting right after a slot delimiter, the result being that packets either collide completely, or do not collide at all. The problematic partial collisions that are observed with Aloha are then eliminated.

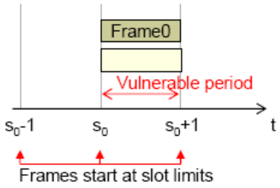

Figure 8: Slotted-Aloha frame vulerability

Assuming the slot length is optimally set to the same size as that of a transmitted frame containing a tag's ID, the period a transmitted frame F is vulnerable to a collision by another tag's transmission is reduced to the slot size F. The disadvantage however, is that such a scheme requires a synchronization mechanism in order for the slot-begin to occur simultaneously at all tags. This is accomplished either dynamically by having the reader send out slot-delimiting beacons, or statically using a pre-defined timer internal to the tags.

The Slotted-Aloha protocols detailed in [iso18000-3, C1G2Spec03] describe extensions aimed to improve performance.

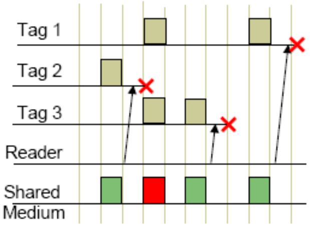

Figure 9: ”Terminating”

The terms "Muting", "Switch-off" and "Terminating" are used alternatively to express the following idea of a `Quiet` state.

The **"Terminating"** extension is similar to the "Switch-Off" method mentioned for Aloha, in that a successfully decoded response leads the tag to automatically enter a `Quiet` state in which it no longer transmits its ID.

The main advantage of tags switching to a `Quiet` state is that unnecessary collisions due to tags replying indefinitely are avoided. Tags in the `Quiet` state re-enter the `Active` state upon the next `Wake-up` command from the reader, which is broadcast at sporadic intervals to account for tags newly arriving in the field. However as is the case with all messages broadcast by the reader, the danger exists that a `Quiet` tag may fail to recognize the reader's `Wake-up` broadcasts [EMMicro98, iso18000-3][2], and would then remain in the `Quiet` state for an indeterminately long time. This is circumvented by having the tags time-out automatically from sleep mode using an internal decrementing counter.

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[2] The radiated RF field and the reflected waves add constructively or destructively, causing nulls and peaks in the RF energy field. A tag in a null will not receive the `Wake-up` command.

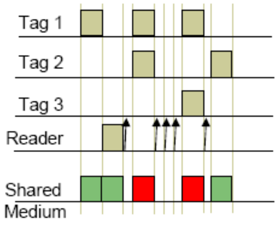


Figure 10: "Early End"

A more interesting extension to the Slotted-Aloha protocol however, is one referred to hereby as **"Early End"**. As described above, the slots are delimited by beacons sent by the reader known as `SOF` (start-of-frame) and `EOF` (end-of-frame). The existence of a delimiting `EOF` beacon allows for Reader-to-Tag commands, which must occur between somewhere between the slots available for tags to transmit.
Upon having sent a `SOF` command to the tags and noticing there are no responses being sent out by tags, the reader can send out an early `EOF` beacon effectively reducing what would have otherwise been dead or wasted time. A silent period caused by the tags randomly waiting out several slots can be reduced to a fraction of the time wasted if all slots were waited out to their full length, thereby reducing the overall tag identification time (when using the "Time-to-last-tag" measure, for example).

2.3 Frame-Slotted Aloha

A Frame-Slotted Aloha protocol is built by taking Slotted-Aloha and the discrete time division one step further by grouping several slots into frames, each frame having N slots.

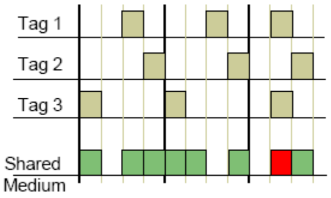


Figure 11: Frame-slotted Aloha example

No significant change is made to the definition of the slot architecture, but the tags are required to transmit exactly once every frame in a randomly selected slot within each frame's N, the number of slots in a frame. Using the previous methods, a tag exhibiting a too high response frequency is pointlessly colliding with potentially valid response from other tags in the field. Frames regrouping several slots implicitly bound this repetitive behaviour by setting a lower-limit to the number of messages a tags transmits to one per frame, and at the same time establishing an upper limit by preventing more than one message being sent per frame. Tag repetitiveness is strongly bounded in a way similar to a system where the reader would repetitively and constantly communicate Slow-down and Speed-up messages to the tags, only static pre-defined frames avoid the extra communication overhead. The extra synchronization overhead required by Frame-slotted Aloha is of the same order of magnitude as for Slotted-Aloha, more so if the maximum slot number N is pre-defined and set in the tags as default. Frame-slotted Aloha being by extension a form of Slotted-Aloha, all of the possible extensions named previously are also applicable. Indeed, more than one Framed-slotted Aloha implementation directly makes use of or provides for Terminating/Muting, Early-End, etc. behaviours.

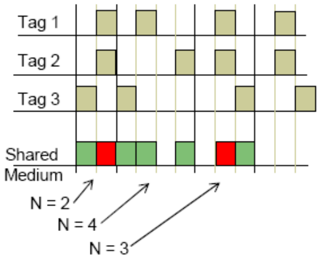


Figure 12: ”Adaptive” Frame-slotted aloha

An extension specifically proposed here is **”Adaptive”** Frame-slotted Aloha. Frame-slotted Aloha’s main parameter being the frame size N, proposes that the reader be able to temporarily expand or contract the number of slots in a frame for the upcoming request round.

The number of slots can then follow approximately the number of tags in the field, either reducing the number of collisions in a frame by increasing the number of slots, or decreasing them if there are too many empty slots. The three factors ”number of collisions”, ”number of successful replies” and ”number of free slots” are combined into a ratio which should determine the most adequate frame-size for the next round of reader listening.

2.4 Summary / Perspective

As the table 1 shows, each of the mentioned protocols can be considered to have its advantages, and its disadvantages. For example, if Aloha is relatively slower and in the worst case could end up not terminating, it on the other hand allows for a much simpler reader design. Frame-slotted is theoretically and also in practice observed to be more efficient at recognizing tags, but requires an exhaustive system design including a more accurate protocol definition and timings than pure Aloha, parallel to which the reader complexity grows.

Aloha	
· easily / quickly adapts to varying number of tags · simplest Reader design: ”listen”	· worst case: never finishes · theoretically proven maximum channel untilisation 18.4%
Slotted-Aloha	
· less of a ”free-for-all” · doubles the channel utilisation of Aloha	· still only 36.8% medium utilisation · requires synchronisation (overhead) · tags need to count slots
Frame-slotted Aloha	
· (automatically) diminishes each tag’s repeat rate to once per frame	· requires synchronisation · ”frame-size” needs to be known / transmitted · tag needs to count frames / slots

Table 1: Overview of protocol advantages and disadvantages

The problem that arises when designing an RFID system, is which collision resolution protocol to choose? The answer is usually not trivial, and strongly depends on the proposed use or application of the system. As an example, a tag identifying system could be confronted with less than 10-20 tags, with the only time constraint being that they be recognized quickly enough that the process is not humanly perceived. The simple Aloha protocol and reader is well-suited for said system. On the other hand, a high-throughput tag-counting system which is typically required to process a multitude of constantly varying tags every second requires strict time constraints, but reader design would be as complex as required to achieve this goal.

3 Existing Implementations

Several RFID systems have been brought to market in recent years, each putting to use one of the above techniques to resolve collisions. The papers, standards drafts, etc. describe the physical layer, media access and command set of the specific systems. The interesting sections for the purposes of this paper, are the descriptions of the media access and collision resolution methods which are for the most part well-described. However some other systems are descriptive, but maintained puposely obscure... they are after all systems meant to be sold commercially.

The examples chosen below were selected because they typify the caracteristics of Aloha-based collision resolution methods described in the first section.

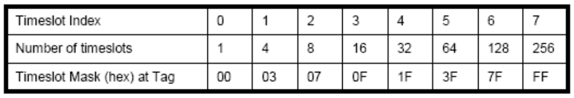
3.1 Philips I*Code

The first commercially available RFID system presented more in detail is the Philips I*Code [icode02], available for the first time in May 1999. This system was chosen as an example because it nicely illustrates the Frame-slotted Aloha protocol and extensions, as well as exhibiting further optimizations not described previously. Due to the limitation of Reader-to-Tag messages that was described in the motivation, the Philipps I*Code implementation optimizes the message size during the process of determining the frame size (number of slots) for the next round. To do so, a table similar to that in Table 2 is used by the tags to calculate the next frame size. The number of slots determined by the reader needs to be relayed to the tags, increasing the amount of messages destined to the tags. As this number of messages can grow quickly, the I*Code system uses an index in a pre-defined table to determine the number of slots in the next round. Since the index is much smaller than the actual number of slots, it can be represented using fewer bits, and the messages from the reader to the tags are smaller.

As with many (slotted) RFID systems, the tags calculate the slot in which to send their unique ID using only pseudo-randomness. Instead of driving the microchip requirements up in the tag, an offset in the tag ID is selected as random number. Very roughly put, the timeslot chosen within the frame is

$$T := hash(offset[ID])\ AND\ TimeslotMask$$

determined using a hash of the ID at the given offset, logically and-ed with a timeslot mask denoting frame-size.



Timeslot Index	0	1	2	3	4	5	6	7
Number of timeslots	1	4	8	16	32	64	128	256
Timeslot Mask (hex) at Tag	00	03	07	0F	1F	3F	7F	FF

Table 2: Table of *TimeslotIndex*es

3.2 ISO 18000-3 "MODE 1"

The default ISO 18000-3 MODE 1 protocol is a deterministic method of querying nodes to avoid collisions, where a MaskValue and MaskLength is sent out alongside a number of slots, and used by the tags to determine the correct response slot in which to reply. However, the standard suggests two optional protocol extensions for collision avoidance, given the tags existing in the reader's field are not always known in advance reducing a deterministic protocl's efficiency.

The first extension is designated as a non-slotted non-terminating aloha protocol, where the tags automatically reply at random with self-determined intervals as long as they are in the reader's scope and energizing field. Once the communications under way, the reader does not in any way dynamically influence the interrogation process. This extension can be considered to be a pure Aloha means of resolving collisions, with the only notable exception that the tags react according to a ”Reader-Talk-First” behaviour, and wait for a broadcast `Wake-Up` signal when exposed to a powering field, before commencing transmitting their IDs.

The second extension proposed is named slotted terminating adaptive round protocol, the equivalent of a Frame-slotted Aloha scheme. This extension provides for a continuing dialog between the reader and tags, where the tags select a reply-slot number, from a maximum slot number. The number of slots in each round expands or contracts with the number of tags in field, as determined by the reader.

3.3 ISO 18000-3 "MODE 2"

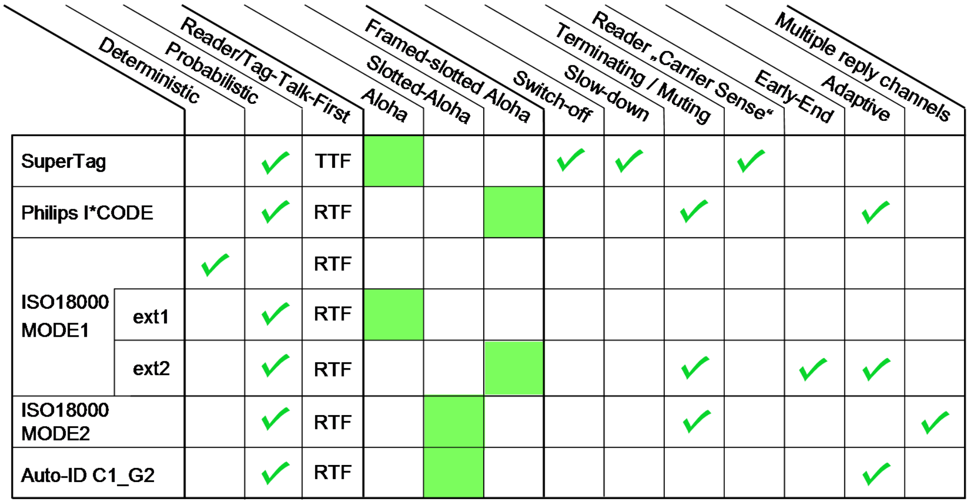
The last protocol considered is once again not an implementation but a standard definition, although the standard has been used as the collision resolution model for Magellan's implementation [magellan01].

ISO 18000 MODE 2 is mentioned here because of the uncommon layer of collision avoidance added to the collision resolution examined previously. The concept behind MODE 2 is a combination of both Frequency and Time Division Multiple Access (FTDMA). A tag following this protocol has the choice of selecting from 8 reply channels to send its ID to the reader. This is possible by dividing the powering field's frequency into 8 subcarriers each on an individual frequency.

The reduced bandwidth for the Tag-To-Reader communications on each of the subcarriers would seem a significant disadvantage to using this method, but since the messages sent are kept minimal, one eighth of the total bandwidth is enough for tags to transmit their IDs. Using terminology adopted from FDMA to describe the technique used by MODE 2, the Frequency Hop Rate is 0 meaning a tags reply is transmitted in its entirety using only one subcarrier. The Frequency Hop Sequence is random due to tags arbitrarily choose one of the subcarriers for their reply. In all other aspects though, MODE 2 follows the Slotted-Aloha behaviour on each subcarrier. An extension to MODE 2 is proposed, namely so-called Muting, which is a combination between silencing the tags and a Slow-Down extension. Although a tag whose response has successfully been decoded can be silenced completely by fully muting it, the standard provides a muting-ratio (unmuted, $\frac{1}{2}$, $\frac{3}{4}$, 31/32, ... , 511/512, fully muted) which the tags use to either mute or unmute individual replies.

3.4 Summary

Figure 2 shows a summary of most collision-resolution methods encountered in the papers that led up to this report, listed in the references as [EMMicro98, iso18000-3, C1G2Spec03, icode02].



		Deterministic	Probabilistic	Reader/Tag-Talk-First	Aloha	Slotted-Aloha	Framed-slotted Aloha	Switch-off	Slow-down	Terminating / Muting	Reader „Carrier Sense“	Early-End	Adaptive	Multiple reply channels
SuperTag			✓	TTF	🟩			✓	✓		✓			
Philips I*CODE			✓	RTF			🟩			✓			✓	
ISO18000 MODE1		✓		RTF										
	ext1		✓	RTF	🟩									
	ext2		✓	RTF			🟩			✓		✓	✓	
ISO18000 MODE2			✓	RTF		🟩				✓				✓
Auto-ID C1_G2			✓	RTF		🟩							✓	

Figure 13: Collision-resolution as implemented in RFID systems

An interesting conclusion to draw from this table is that no particular algorithm seems to emerge as the preferred method to resolve collisions. The choice of algorithm for implementation in systems aimed for the market is fairly well distributed between Aloha and its two derivatives. Also apparent is that most systems encountered implement at least one of the extensions mentioned, and only select few such as the ISO18000 MODE 1 implement none. This is a possible indication that most implementers deem a direct mapping of the algorithms to practice too inefficient.

4 Comparative Analysis

4.1 Comparison problems

When attempting to compare systems to one-another, an important problem appears: the descriptions and performance evaluations offered in all papers use varying metrics to assess tag recognition performance. Those encountered the most are the Mean Access Time for a tag, the Transaction Speed (tags/sec) or Time-to-Last-Tag, but none are widespread enough to allow a suitable comparison. All-in-all, most papers of a technical nature have thorough test data and appreciable results that appear to stand ground, but using figures from one paper to put up against those from another is often meaningless due to this lack of standard and common measure. Another misleading fact is that all tag systems are not similar in design. One has to consider when comparing systems that several important factors vary from system to system, such as the tag ID length, or the data rates used in the system. Trade literature is often incomplete or could even be misleading, the main reason being namely that the systems are meant to be sold, and that underperforming numbers could frustrate a systems ability to generate revenue. For this same reason manufacturer's websites are light on technical details, but heavy on marketing information.

As a result, comparing systems to one-another can be very difficult, challenging or even meaningless in some cases.

4.2 ISO 18000 "MODE 1" vs. "MODE 2"

In this next section, an example of comparison between two systems will be chosen from a document by Magellan purporting to put ISO 15693 and ISO 18000 MODE 2 head-to head under test conditions similar to ”real world” applications. The comparison is rendered possible because both the MODE 1 and MODE 2 standards define Time-to-Last-Tag as a measure of their efficiency. The goal of the tests performed is for each system to identify 500 tags placed within the readers range, and read 100 Bytes of data from each tag. The total time to identify all 500 tags, and read data from them is the measure used to evaluate both systems.

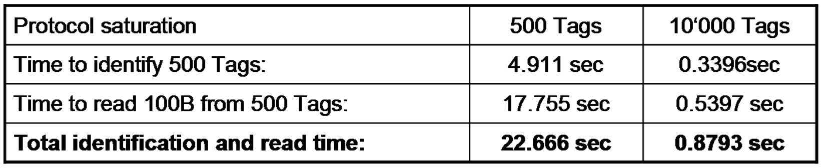
In order to simulate a real world scenarios, a matrix of four test setups was imagined, with the tags orientation and numbering as parameters:

- Randomly oriented, same fixed orientation;
- Randomly numbered, sequentially numbered;

These criteria, orientation and numbering, are based on the following observations:

- The tag’s orientation with respect to the transmitting antenna affects the reading range and consequently achievable read rates. The signal strength received by randomly oriented tags varies, and can be the cause of weak collisions in which data that would normally be lost to a collisions can be read because one tag has overpowered the other.
- The tags use an offset from their IDs to determine the slot in which to transmit an identificating number, meaning sequentially numbered tags choose the same or slots close apart and cause an irregularly high number of collisions.

In the example of randomly numbered, randomly oriented tags, the Table 3 summarizes the results observed.



Protocol saturation	500 Tags	10‘000 Tags
Time to identify 500 Tags:	4.911 sec	0.3396sec
Time to read 100B from 500 Tags:	17.755 sec	0.5397 sec
Total identification and read time:	**22.666 sec**	**0.8793 sec**

Table 3: ISO18000 MODE1 - MODE2 comparison [magellan01]

To offer explanations for the test results, one has to further examine the systems in question. Surely, the eight subcarriers for tags to choose from for their response contributes greatly to better times of MODE 2 because of a much better effective data rate, without ignoring also that MODE 1 uses half-duplex operation limiting performance when the number of tags is large. Indeed commands and replies must occur sequentially in with MODE 1, whereas commands can occur simultaneously witout interference in MODE 2’s eight subcarrier full-duplex system. Furthermore, the MODE 2’s data rate is with 105.94kb/s nearly four times greater than MODE 1 with 26.69kb/s.

Added explicitly in Table 3, is the theoretical protocol saturation put forth by the standards definitions. By reading from 500 tags, the test scenario nears dangerously the limit after which MODE 1 ceases to be linear and recognition time becomes polynomial, whereas saturation in MODE 2 lies much higher at 10’000 tags. Lastly, to paraphrase the Magellans deductions, MODE 1s anti-collision algorithm cannot tolerate new tags entering the field once an identification cycle has started [magellan01], severely limiting performance. The conclusion that is however offered is that identifying and reading data from a large number of tags is 26 times faster with the MODE 2 protocol, as with MODE 1.

4.3 Counter-Example

As a demonstration meant to show how the above comparison's scope and significance is limited, one needs only to look at the Philips I*Code system presented in section 3. The Philips I*Code system literature [icode02] uses the Mean Access Time to convey the speed and overall performance.

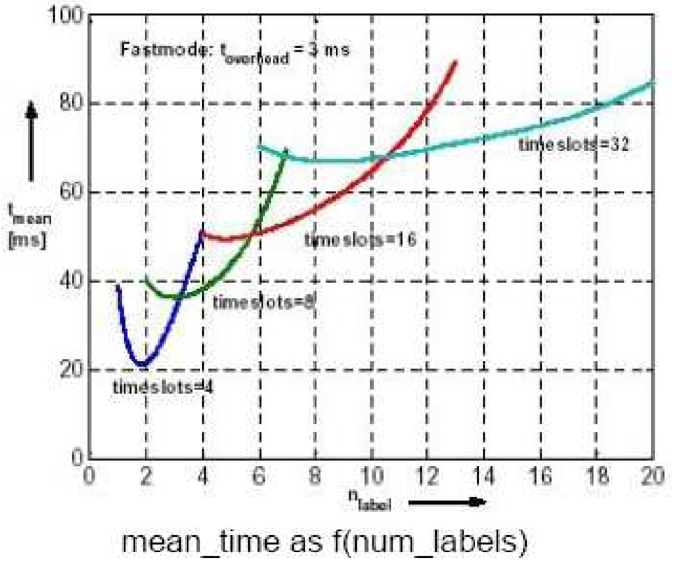


Figure 14: I*Code: mean_time as f(num_labels)

The figure 10 shows for example how the Mean Access Time is influenced by the number of labels in the field, in terms of the number of slots. The Mean Access Time however, happens to depend heavily on the optimal frame size for a given number of tags. Since the I*Codes determination of slot numbers varies only by powers of 2, the optimal slot number lies somewhere within

$$2^{current-1} \leq optimal \leq 2^{current}$$

where current is the actual frame size index. Having too little timeslots in a frame causes too many collisions, whereas too many timeslots lead to wasted blank times that add to the Access Time. What's more, the optimal number of timeslots itself depends heavily on the number of tags actually in the readers field, and the reader incurrs a delay when determining and changing the number of slots to be better suited.

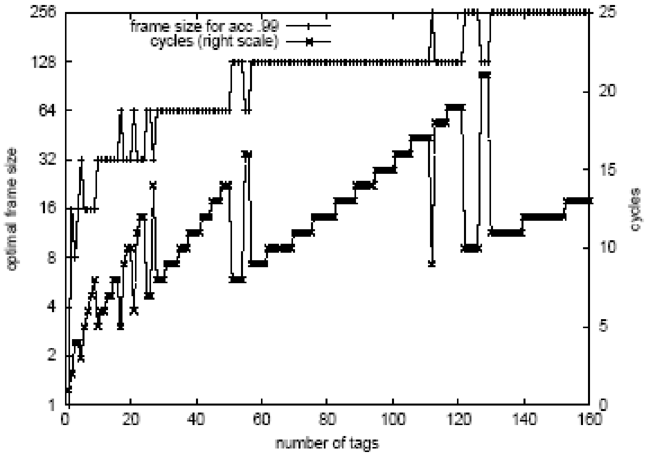


Figure 15: optimal frame size as f(number of tags) [Vogt02]

As is explained in [Vogt02], the optimal framse size is not discretely palletized (figure 15), and there exist "transition periods" where more than one frame size is optimal, determined using an extimation of the number of tags in the field. A good algorithm will avoid too much overhead and give suitable intervals for which a certain frame size is reasonable, instead of changing constantly within these transition periods.

For the reasons above, tests involving the I*Code system are often done on a repeated basis, where several iterations under the test conditions are carried out. The choice is then open as to whether the best, the average or the median of all test runs is used as the determining value. No one measure for the I*Code system can thus be taken as the measure to compare it against other systems. The conclusion to draw from this is that for one given protocol, minimal changes in the implementation or the circumstances of each run can change the resulting data and measures greatly, in all probability to the point of rendering comparison to another system without significance.

5 Conclusion

The challenge that emerges for RFID systems where multiple tags are present in the reader's field is maximizing the number of tags accessed for information, while simultaneously minimizing the time needed to do so. The first section dealt with qualitatively distinguishing the derivatives of the Aloha protocol, and presenting adaptations thereof particularly well suited for problematic RFID systems. An attempt was made in the second section to show a quantitative approach at classifying RFID systems, and comparing the implementations of the Aloha protocols, while at the same time exposing the problem of a lacking common metric that emerges while doing so.

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