Analysis of RFID anti-collision protocols based on the standard EPCglobal Class-1 Generation-2

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***Abstract*—Radio Frequency Identification (RFID) technology is undergoing a remarkable development in the last few years. In this technology, identification information is exchanged between two devices: readers and tags. If two tags attempt to transmit simultaneously, a collision is produced. This phenomenon, known as the tag collision problem, is becoming increasingly important, since it leads to an increase in the reader transmitted bits and identification delay, in addition to a wastage of energy and bandwidth. In this context, protocols based on the EPCglobal Class-1 Generation-2 (EPC C1G2) standard arbitrate collisions by adjusting the transmission frame size. The standard presents an uncertainty in the selection of the frame size, since it does not specify the exact value. This has led to many different alternatives. This paper analyzes the most relevant anti-collision protocols which deal with this uncertainty, taking into account the limitations imposed by the standard EPC C1G2.**

I. Introduction

The growing concern in tracking, identification and localization systems has turned Radio Frequency Identification (RFID) technology into a mainstream in scientific research. This technology is especially attractive in areas like health care, supply chain, e-passports, and wireless sensor networks [1] [2] [3]. RFID is a wireless ubiquitous technology, where a spectrum of radio frequency is used to transfer the identification information between two communication devices: tags and readers. The main advantages of this technology are that it does not require human intervention to read data, a direct vision line between reader and tags is not necessary, and it provides robust and secure identification systems. Tags are uniquely identified with an identification code (ID), which consists of a sequence of bits. Due to the shared nature of the wireless channel used by tags, these systems are prone to transmission collisions. A collision occurs when two or more tags transmit information simultaneously. Collided tags must retransmit their IDs until they are identified, resulting in a wastage of bandwidth, energy, and an increase in the identification delay and reader transmitted bits [4]. Anti-collision protocols are hence required to arbitrate these collisions.

Broadly, anti-collision protocols can be categorized into, space division multiple access (SDMA), frequency division multiple access (FDMA), code division multiple access (CDMA), and time division multiple access (TDMA) [5]. Briefly, systems based on SDMA spatially separate the channel using multi-directional antennas or multiple readers to identify tags. FDMA involves tags transmission in one of the several predefined frequency channels. CDMA requires tags to multiply their ID with a pseudo-random sequence before transmission. Lastly, TDMA divides the transmission channel into time slots so that if there is only one tag response in one slot, the reader can identify the tag correctly. TDMA constitutes the largest group of anti-collision protocols [4].

Inside TDMA, anti-collision protocols can be categorized into Aloha based, tree based and hybrid protocols [5]. Tree based protocols successively split collided tags into two or more subsets and the reader attempts to recognize each one of the subsets one by one [6]. Aloha based protocols divide time into slots and tags randomly choose one slot to respond [7]. Aloha based protocols present four main variants [5]. In Pure Aloha (PA), a tag will respond to the reader command randomly after being energized. Slotted Aloha (SA) divides time into slots and schedules tags to respond only at the boundary of the time slots. Frame Slotted Aloha (FSA) and Dynamic Frame Slotted Aloha (DFSA) divide time into frames and frames into slots and mandate each tag to respond only once per frame. While in FSA the frame size is fixed during the identification process, in DFSA it is variable. The fact that the standard EPCglobal Class-1 Generation-2 (EPC C1G2) currently uses a DFSA structure to arbitrate collisions, highlights the relevance of this scheme. Finally, hybrid protocols combine the advantages of Aloha based and tree based protocols [8].

The current standard in RFID systems is the one defined in the EPC C1G2 protocol (also included in the standard 18000-6C) [9]. EPC C1G2 employs a DFSA protocol to arbitrate collisions: the Slot Counter protocol, commonly known as the Q-protocol. This protocol controls the tags identification process based on the number of tags in the system and their responses to the reader's queries. In order to arbitrate the process, the reader updates the transmission frame size dynamically. In this context, a transmission frame is defined as a sequence of time slots where tags can only respond once. Conventionally, a slot comprises the time from the point that the reader sends a command to the point that the tags finish replying their temporary IDs [10]. In this respect, the parameter Q is defined to update the frame size. This parameter is updated according to the value of C. Therefore, C represents a key element for the protocol performance, since it ultimately determines the transmission frame size.

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The standard does not specify the selection of C. It only recommends using high values if the previous Q value was low and vice versa, in the range of $[0.1, 0.5]$. This lack of definition has led to many different alternatives.

A simple solution found in the literature is setting C to a fixed value for the whole identification process [11]. A different approach is assigning C according to the current Q value [12] [13]. Additionally, a third possibility found is giving two different values to C depending on whether the current slot results in idle or collision response [11] [14] [15].

In this context there are several papers in the literature on the most relevant DFSA protocols. For example, in [16] the presented protocols are classified according to four different factors, not related to our analysis. However, not all the compared algorithms use the parameter C specified in the standard to update the frame size. In [17] several anti-collision protocols and multiple reader coexistence are studied. Nevertheless, the studied algorithms are currently of minor interest since they are not EPCglobal compliant. The work [18] surveys some DFSA protocols while simulating the throughput and estimation error. But, again, they do not adopt the EPCglobal constraints. In [19] the authors examine the pros and cons of different anti-collision protocols, but they only examine one Aloha-based protocols, which does not employ the C parameter either.

This paper focuses on the analysis of the C parameter, which had not been studied in the mentioned previous work. Several anti-collision protocols based on the Q-protocol are then analyzed in terms of this parameter. They all have in common the use of the parameter C to arbitrate the identification process. This parameter is considered of great importance regarding the protocol performance, since it ultimately determines the transmission frame size. Moreover, the presented protocols are compared regarding two parameters not considered before: the box blot and the protocol stability. In this context, simulations analyze the performance of the protocols in terms of slots efficiency, protocol accuracy and reader transmitted bits

Subsequently, the remainder of this paper is organized as follows: Section II describes an overview of the standard; Section III presents the comparative protocols; Section IV shows a comparison of the previously presented protocols and the simulations results; and finally, Section V concludes the paper.

II. Anti collision strategy in EPCglobal Class-1 Generation-2

The fact that most RFID manufacturers currently follow the EPC C1G2 standard highlights the research relevance of this protocol [7]. The standard EPC C1G2 employs a DFSA protocol to arbitrate collisions, the Slot Counter protocol, commonly known as Q-protocol. It specifies the transmission frame size (L) as a power of two, taking the value $L = 2^Q$, where $Q \in \mathbb{N}$ and $0 \leq Q \leq 15$. It also defines the parameter Q_{fp} to update the frame size, where $Q = round(Q_{fp})$. Fig.1 shows a flux diagram of the Q-protocol employed in the standard. The reader starts the identification process by

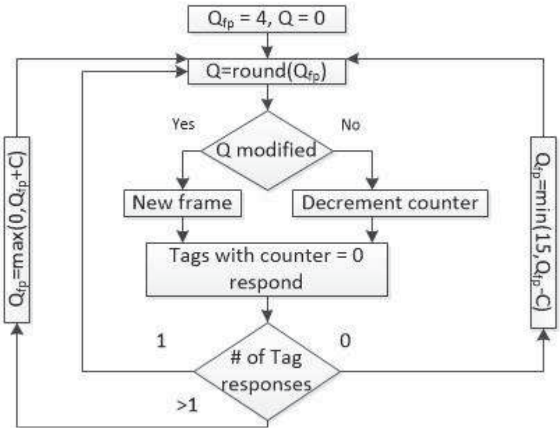

Fig. 1: Q-protocol flow chart

broadcasting a Query command and specifying the initial value of Q. This command is exclusively broadcast at the beginning of the identification round (first slot of the first frame). The reader then alternates between QueryAdjust (QA) and QueryRep (QR) commands to identify the set of tags. QA starts a new frame and implies tags to randomly select a slot in the frame, while QR tells tags to decrement their internal slot counter. The reader starts a new frame by broadcasting QA with the corresponding L. Then each tag randomly chooses an integer from 0 to $L-1$, and update their internal slot counter with it. Those generating 0 contend the channel in the current slot by sending a randomly generated number of 16 bits length ($RN16$). Regarding the time slot occupancy, there are three possible scenarios to update the value of Q_{fp}:

- None of the tags replies. The slot is considered idle and $Q_{fp} = Q_{fp} - C$.
- Only one tag replies. The slot is considered single response and Q_{fp} remains unchanged. In this case, the reader replies the tag with an ACK command followed by the same $RN16$ received by the tag.
- More than one tag replies. The slot is considered collided and $Q_{fp} = Q_{fp} + C$.

Next, the reader readjust the frame size to $L = 2^Q$ where $Q = round(Q_{fp})$. At this point, according to [13] the reader can follow two strategies. The first one is to send a new QA and thus starting a new frame with the updated frame size only if the slot counter reaches the last slot of the frame. The second strategy, called *slot by slot*, consists on sending a QA every time Q is modified, independently of the number of remaining slots in the frame. In any case, if the condition for broadcasting a QA is not satisfied, a QR is sent instead, asking the tags which have not transmitted in the current frame to decrement their internal counter by one. Collided tags wait for the reader to send a QA. Finally, identified tags go into sleep mode and leave the reading process. This procedure repeats until all tags have been identified. The *slot by slot* strategy has been followed for all the comparative protocols in this paper, since according to [13], it provides a better performance.

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III. Analysis of Q-protocol variants

As can be inferred, the Q parameter plays a significant role in the Q-protocol, so it should be carefully chosen. If Q is relatively large in relation to the number of unidentified tags and the tag set is small, the likelihood of idle slots increases. On the other hand, if Q is relatively small in relation to the number of unidentified tags while the tag set is large, the likelihood of collided slots increases. Moreover, since the value of Q is determined by the value of C, the selection of C is a key step in the protocol. According to [4] [15] [20] [21], the optimal L maximizes the slots efficiency when the number of unidentified tags is equal to L. Therefore, Q-based anti-collision protocols must adopt an strategy to select C in order to dynamically adjust the frame size so that it approaches the optimal value. Three main strategies to select C can be found in the literature. An intuitive solution is setting C to a constant value. Moreover, C can be chosen according to the current value of Q. Finally, the value of C can also be determined regarding the state of the current slot (collision, idle or success). According to this classification, table I shows the main proposals.

TABLE I: Clasification OF Q-PROTOCOL-BASED ALGORITHMS

Strategy	Protocol
C fixed	*C=0.2* *C=0.5*
$C = f(Q)$	optimalC $C = 0.8/Q$
C = f(slot state)	fastQ Q+ SCS

A. Fixed C

A simple solution found in the literature is fixing the value of C during the complete identification process [11]. In this paper a low value $C = 0.2$ and a high value $C = 0.5$ are chosen for the comparison, both falling inside the range specified in the standard. Giving C a value of 0.5, the protocol performs better when the frame size L, controlled by Q, is relatively low in relation to the number of unidentified tags. On the other hand, if C is set to 0.3, it performs better when the frame size is relatively high. Therefore, a balance between low and high C values must be sought.

B. C as a function of Q

A different strategy to update the frame size is setting C according to the current Q value. A protocol which outputs different C values within a range (optimalC) is presented in [12]. They claim to obtain C from the simulation results for different frame sizes (or Q values) in the sense of minimizing the identification time. For this purpose $C \in [0.1, 0.5]$, and it can only take values in 0.1 steps (5 different possible values). The value of C is chosen regarding that the higher the value of Q, the lower the value of C. However, their results are not conclusive, since the authors only compare optimalC with the Q-protocol with fixed frame size (Q does not change during the process of tag identification). Table II shows the value of C as a function of the frame size up to a population of 1024 tags [12]. In [13] it is suggested to establish $C = 0.8/Q$ based on empirical results, although the authors claim to obtain poor results with this strategy.

TABLE II: VALUE OF C AS A FUNCTION OF FRAME SIZE

Q	Frame size	*C*
1	2	0.5
2	4	0.5
3	8	0.5
4	16	0.5
5	32	0.5
6	64	0.5
7	128	0.4
8	256	0.3
9	512	0.2
10	1024	0.2

C. C as a function of the current slot state

A different approach to select C is based on the current slot state (collision, idle or success). The Fast Q protocol (fastQ) presented in [14] introduces two different values for C to avoid unnecessary collided or idle slots. If the reader detects a collision C takes the value C_{col} while if the reader detects no response, C takes the value C_{idle}. They claim that C_{col} and C_{idle} should be proportional to Tr and Pr, where Tr represents the ratio between the time duration of a collided slot and idle slot and Pr represents the ratio between the probability of a collided slot and an idle slot. Consequently they establish the following ratio:

$$C_{col}/C_{idle} = Tr * Pr = 1.4122 \tag{1}$$

Similarly, the protocol presented in [15] (Q+) also separates C into two values, C_c for collided slots and C_i for idle slots. Both values are defined in order to optimize the efficiency of tag identification, setting the optimal ratio as $C_c/C_i = e - 2$. The authors also provide a formula to obtain the two variables regardless if the number of tags is known or not, although they do not indicate the tag estimation procedure.

In [11] C is also replaced by two new variables: $c1$ for collided slots and $c2$ for idle slots. The presented protocol (SCS) obtains $c1$ and $c2$ slot by slot as a function of other parameters that mainly depend on *reader-to-tag* and *tag-to-reader* data rates. It is suggested to set $c2 \in [0.1, 1]$ and $c1 = 0.1$ claiming that it greatly improves the performance in comparison to the Q-protocol with fixed C value. Specifically, $c2$ is selected as follows:

$$c2 = min(1.0, c1 * \overline{T_{coll}}/\overline{T_{idle}}) \tag{2}$$

where $\overline{T_{coll}}$ and $\overline{T_{idle}}$ represent the average duration of a collided reply and no reply respectively.

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IV. PERFORMANCE EVALUATION

This section presents the results of the simulation experiments using Matlab R2013a. The performance of the protocols presented in the previous section has been evaluated. The proposed simulation defines a scenario with one reader and a varying number of tags, n, from 100 to 1000 tags with a step size of 100. It is assumed that the transmission channel is ideal and the tags' slot selection is uniformly distributed along the frame [7] [11] [12] [14]. The simulation responses are averaged over 1000 iterations for accuracy in the results. For all the simulated protocols in the comparison, it is assumed that the identification procedure ends when all tags have been identified. Table III shows the values of the parameters used for the simulations according to the standard specifications [9].

TABLE III: TYPICAL SYSTEM PARAMETERS OF EPC C1G2

Parameter	Value
Length of Query (lq)	22 bits
Length of QueryAdjust (lqa)	9 bits
Length of QueryRep (lqr)	4 bits
Length of ACK ($lack$)	18 bits

A. Simulations assumptions

Some algorithms leave some parameters open. In those cases, the following is assumed:

- Q+ protocol: the computing methodology for C_c is unknown. The authors only state that $C_c \in [0.1 - 0.5]$. Therefore, it is assumed $C_c = 0.35$, leading to $C_i = (e-2) * C_c = 0.2514$.
- SCS protocol: $c1$ and $c2$ are computed assuming the typical values of the standard specified in [22]. Herein, the values $c2 = 0.1253$ and $c1 = 0.1$ are employed.

They show that Q updates faster when a collided reply occurs than when there is no reply

B. Slots efficiency

For tags identification protocols, the slots efficiency is defined as the ratio between the number of tags and the number of time slots required to identify them [23]. Results are shown in Fig.2. SCS and fastQ, followed by $0.8/Q$ show the highest slots efficiency. Besides, it can be observed an increase of the slots efficiency with the tag population in all cases except for $C = 0.5$, where it decreases. Moreover, for Q+ the slots efficiency remains approximately constant. The fact that the efficiency decreases with tag population for $C = 0.5$ is due to the high value of C in relation to the tag populations analyzed. This relative high value leads to oscillations of the frame size in order to adapt to the number of unidentified tags, resulting in an higher average number of total time slots. Additionally, the protocol with $C = 0.5$ also presents a considerably higher number of collided slots, as shown in Fig.3. From this figure, it can be concluded that setting C according to the current slot state leads to a lower number of collision slots compared to the other two strategies presented, since fastQ, Q+ and SCS show a better performance regarding this parameter. It can also be appreciated that for this strategy, the higher the ratio $C_{collision}/C_{idle}$, the lower the number of collided slots. To corroborate this fact, this ratio has been obtained for the three protocols inside this category:

- fastQ: $C_{collision}/C_{idle} = 1.4122$
- Q+: $C_{collision}/C_{idle} = 1.3922$
- SCS: $C_{collision}/C_{idle} = 1.2530$

A higher ratio means that the frame is being widened at a higher pace than it is being narrowed. This leads to a decrease of collisions slots as this ratio increases, since a higher weight is given to collided slots in relation to idle slots.

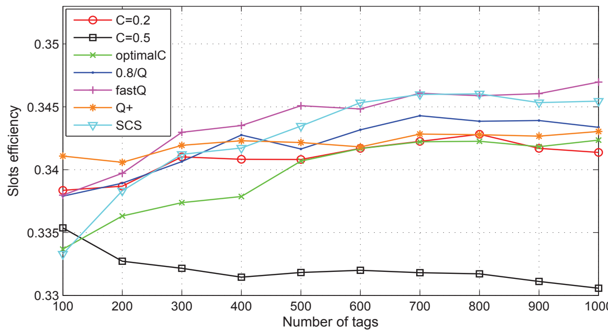

Fig. 2: Slots efficiency

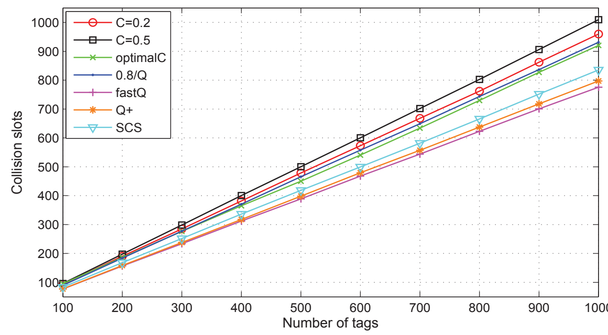

Fig. 3: Collision slots

C. Protocol accuracy

As far as we are concerned, the analysis of the boxplot has not been employed before to study the number of slots in DFSA protocols. The study of the boxplot enables an precise observation of the protocol accuracy by breaking the analyzed data set into four quarters, where the data set considered here is the total number of slots. In this, a boxplot is shown in Fig.4 for a population of 40 and 400 tags. These values have been selected in order to study the effect over greatly different tag populations. 1000 iterations have been employed for accuracy in the results. It is considered that the whiskers (dashed lines extending from the central box) extend to $w = 1.5$

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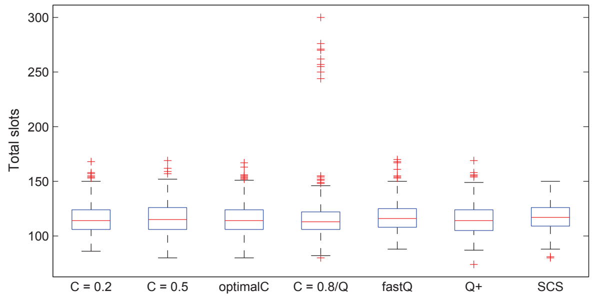
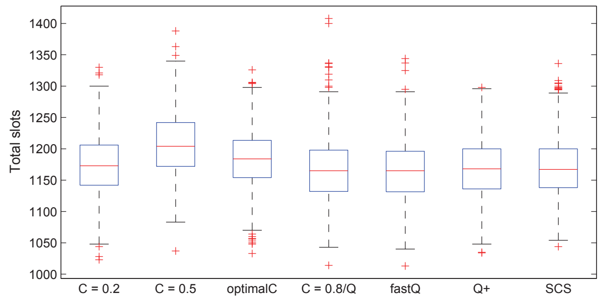
times the height of the central box. Additionally, points are considered outliers (crosses outside the box) if they are larger than *q3+w(q3-q1)* or smaller than *q1-w(q3-q1)*, where q1 and q3 are the 25th and 75th percentiles, respectively. Fig.4a shows a symmetry in the number of slots for all protocols except for $0.8/Q$ since the median appears approximately in the middle of the box. In the case of $0.8/Q$, it appears slightly under the median, involving that for more than half of the iterations, the total number of slots obtained is lower than the average. Moreover, for $0.8/Q$ there are more outliers, which means that it presents a higher dispersion than the comparative protocols. Fig.4b studies the quartiles for a population of 400 tags. Results shown are similar to those examined for the population of 40 tags in Fig.4a. However, here all protocols including $0.8/Q$ present symmetry. Besides, Q+ shows a clear lower dispersion than the comparative protocols, since it only presents three outliers for both tag populations. Q+ would be the best choice for slot-dispersion-sensitive RFID systems, since it presents the lowest number of outliers points. Therefore, Q+ can be considered as the most accurate protocol in terms of slots. The box plot also provides information about the total number of slots. Considering both examined tag populations, all protocols present a similar box height. Data inside the box represent the 50% of the data set. In this, $C = 0.2$, $C = 0.5$ and optimalC, present a lower performance since the box is located above the rest, meaning that half of the iterations of these three protocols output a higher number of slots than the rest of the comparative protocols. This factor is even more noticeable for the population of 400 tags. Therefore, the strategy which updates the frame size according to the current slot provides a better performance regarding the total number of slots.



(a) Quartiles for 40 tags



(b) Quartiles for 400 tags

Fig. 4: Boxplot of total number of slots

D. Reader transmitted bits

The reader transmits three main types of commands to identify a set of tags: Query, QA and QR, as mentioned in Section II. Additionally, when the reader receives a response from exclusively one tag (successful identification), it sends back an ACK command followed by the same RN16 received from the tag. Therefore, the total number of reader transmitted bits can be obtained as follows:

$$R_{bits} = lqa * tQA + lqr * tQR + n * (lack + RN16) \quad (3)$$

where lqa, lqr, $lack$ and $RN16$ are defined in table III, n represents the number of tags in the system, and tQA and tQR represent the total number of QA and QR sent by the reader, respectively. Fig.5 presents the total number of reader transmitted bits, where all protocols show similar values. SCS and $0.8/Q$ show the lowest number of bits, while $C = 0.5$ shows the highest. The number of QA and QR commands sent by the reader determines ultimately the total number of reader transmitted bits since all the other parameters in (3) (laq, lqr, n, lac, RN16) are fixed for all protocols. This influence is analyzed in Fig.6, where the stability factor (SF) is shown. This metric is defined as the ratio between the total number of QR and the total number of QA sent by the reader:

$$SF = QR/QA \quad (4)$$

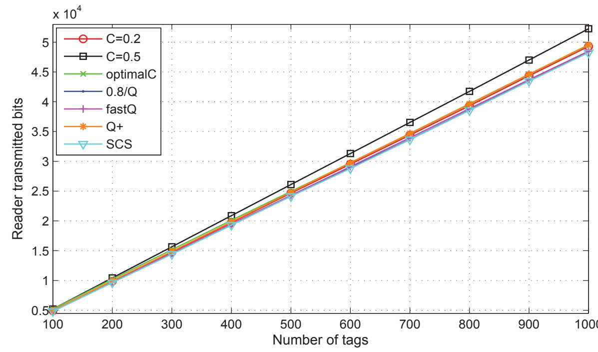


Fig. 5: Reader transmitted bits

This factor provides information about the number of time slots employed for starting a new frame in relation to the number of slots used to decrement the slot counter (the reader keeps the current frame). This factor is desired to be as high as possible, since the length of QA is slightly higher than double the length of QR. In Fig.6 it is shown how SCS presents a much higher value of SF than the comparative protocols, justifying the lower number of the reader transmitted bits obtained in Fig.5. Considering the stability factor defined above and the box plot analysis, it can be said that SCS is the most stable protocol, since it presents the highest SF value while keeping a low dispersion (low number of outliers). On the other hand, the protocol with $C = 0.5$ constitutes the least

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stable, presenting the lowest SF.

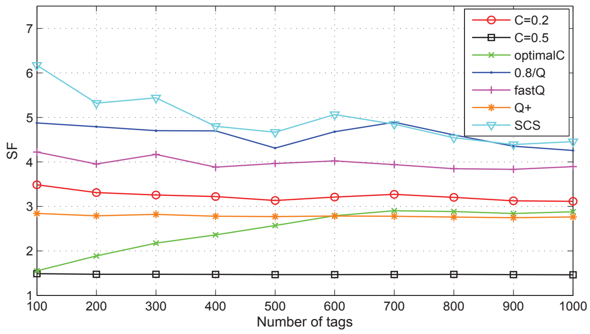

Fig. 6: Stability factor

V. Conclusion

Relevant results have been achieved regarding current DFSA proposals. To conclude, some outcomes are presented. Three main strategies are found in the literature to determine the value of C in the Q-protocol. The strategy where C = *f(slot state)* presents the lowest number of collided slots. Inside this strategy, the higher the ratio $C_{collision}/C_{idle}$ the lower the number of total collided slots. Moreover, SCS and fastQ, belonging to this strategy, present the highest slots efficiency. Regarding the boxplot, all protocols in the comparative show a symmetric distribution in the total number of slots for large tag populations (around 400 tags). Analyzing this parameter, 0.8/Q presents the highest dispersion. In relation to stability, the SCS constitutes the most stable protocol as it presents a higher value of SF in relation to the comparative protocols while keeping a low dispersion. Overall, it can be stated that the selection of C greatly influences the Q-based protocols' performance, so it should be carefully chosen regarding the specific application. As a concluding remark, some future work is presented. The standard suggests $L = 4$ as the initial frame size. However, this parameter greatly influences the protocols performance. Future work could lead to the study of the effect of the initial frame size over the performance of the presented protocols. Moreover, the comparison between the strategies which update the frame size using C and Q with those estimating the tag population would also be a relevant future comparative.

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