Fast fuzzy anti-collision protocol for the RFID standard EPC Gen-2

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A new methodology which integrates fuzzy logic with RFID anti-collision protocols is proposed. The resulting FuzzyQ protocol significantly decreases the identification time by updating the transmission frame size in a dynamic and adaptive way. Simulation results show the performance of FuzzyQ compared with earlier protocols based on the standard EPC Gen-2.

Introduction: RFID technology is becoming popular in asset identification, tracking, and localisation applications, greatly increasing the density of available tags in interrogation zones. The coexistence of tags sharing the same communication channel requires solutions to handle collisions. Anti-collision protocols are sought to mitigate the degradation of the reader's bandwidth, its power consumption, and the delay caused by collisions.

EPCglobal Class 1 Generation 2 (EPC C1G2) [1] is the current standard in RFID systems. EPC C1G2 employs the Slot Counter protocol to arbitrate collisions, commonly known as the Q-protocol. A key feature of the Q-protocol is the frame size (L), which is dynamically updated by means of the parameter named Q ($L = 2^Q$). To manage the identification process, the reader begins with transmitting a Query (Qc) command, and then alternates between QueryAdjust (QA) and QueryRep (QR) commands. QA starts a new frame with the updated size and arranges that the tags randomly select a slot in the frame [the initial value of their internal slot counter (SC)], whereas QR tells the tags to decrement SC. Thus, when SC = 0, the tag transmits a 16 bit random number (RN16); and once it is acknowledged, the tag transmits its IDentification code (ID).

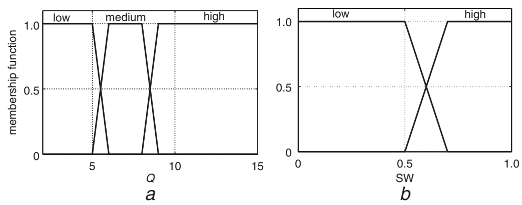

Fig. 1 *Input membership functions for FuzzyQ*

a Q
b SW

The lack of definition about the function to update Q has led to many different alternatives. Several papers can be found in the literature which deal with the parameter Q to update L [2, 3]. Most protocols are based on a smooth increase in L. Therefore, when the collision or idle rate is high, they must employ a relatively high number of slots and reader and tag bits to find an appropriate L. Moreover, the examination of L at every slot results in an increase in the protocol's identification time (IT). The solution presented in [3] suggests examining L at just one slot per frame, set at L/i, $i \in [4, 2, 4/3]$, claiming to significantly reduce the number of total examination points. However, this protocol is based on tag estimation, being restricted to a maximum tag population of 1420 tags. Moreover, the estimation behaves poorly at the early and final stages of the identification process, limiting the protocol's performance.

The aim of this Letter is to apply fuzzy logic to the Q-protocol in order to lower the IT by effectively updating L. Fuzzy logic has already been applied to RFID systems, in areas such as security and antennas design. Nevertheless, to the best of our knowledge, this is the first time that it has been employed to model an RFID anti-collision protocol.

To evaluate the proposed protocol, a novel performance metric is introduced, the stability factor (SF). The metric of the number of slots has been widely employed in the literature. However, it lacks relevant information, since different slots can have different durations. For the purpose of considering this effect, the parameter SF is defined and evaluated for the comparative protocols, providing information about the rate of introducing new frames.

Proposed FuzzyQ protocol: A fuzzy rule-based system (FRBS) is applied to the Q-protocol in order to adjust L, resulting in what we call the FuzzyQ protocol. This protocol models the current L and the slot waste (SW), which represents the idle or collision response rate, as fuzzy sets to adaptively update the value of Q. A zeroth-order Takagi–Sugeno–Kang fuzzy system with a complete AND-composed rule [4] is proposed. The membership functions used to codify the input variables are trapezoidal and the *t*-norm minimum is used to implement the AND operator. The proposed system (see Fig. 1) has two inputs:

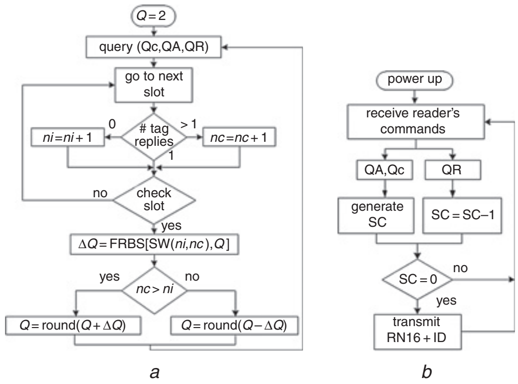

Fig. 2 *Flow diagram of FuzzyQ*

a For reader
b For tags

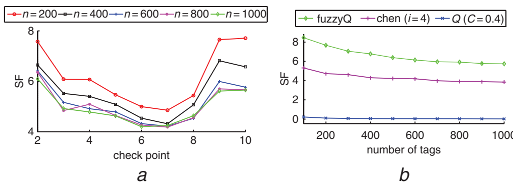

Fig. 3 *CP selection for FuzzyQ, and comparison with Chen(i = 4) and Q(C = 0.4) for CP = 9*

a Effect of *check point* over SF
b Evaluation of SF

- SW: codifies the idle or collision response rate and it is defined as follows: $\text{SW} = \max(ni, nc)/\text{slot\_pointer}$, where nc and ni represent the total number of collisions and idle responses in the current frame, respectively, up to and including the current slot.
- Q: codifies the current value of this parameter which determines L, where $Q \in \mathbb{N}$ and $2 \leq Q \leq 15$.

Examining SW, it represents the number of idle and collision slots in relation to the total number of slots, assuming that the tags' slot selection is uniformly distributed along the frame. Additionally, the variable *slot_pointer* represents the reader's internal counter, which keeps track of the present slot in the current frame. As shown in Fig. 1, both input variables are codified with an initial number of trapezoids: two for SW and three for Q. Values outside the range are assumed to be equal to the corresponding limit, thereby offering maximum coverage. The output ΔQ represents the variation of Q, and it is codified by three singletons with four possible values: Null = 0, Low = 1, Medium = 2, and High = 3. The rule set of the FRBS is composed by six rules:

- Rule 1: IF (Q is Low) AND (SW is Low) THEN ΔQ is Low.
- Rule 2: IF (Q is Low) AND (SW is High) THEN ΔQ is High.
- Rule 3: IF (Q is Medium) AND (SW is Low) THEN ΔQ is Null.
- Rule 4: IF (Q is Medium) AND (SW is High) THEN ΔQ is Medium.
- Rule 5: IF (Q is High) AND (SW is Low) THEN ΔQ is Null.
- Rule 6: IF (Q is High) AND (SW is High) THEN ΔQ is Low.

Rules were designed considering, on the one hand, the higher the frame size, the lower the increment of Q; and on the other hand, the higher the idle or collision rate, the higher the increment of Q.

Once designed, the FRBS is employed to determine the variation in the previous frame size (L) of the Q-protocol. FuzzyQ seeks to lower the IT of the Q-protocol employed in the standard EPCglobal by introducing the two following strategies: (i) to check whether the current L is appropriate given the values of SW and Q at strategic slots and not at every slot. These slots, called *check slots*, are distributed one per frame. The *check slot* is defined as L/CP, where CP stands for *check point* and CP $\in \mathbb{N}$. (ii) Not limiting the variation of Q to steps of one unit and to consider instead a range of values, in order to achieve a more abrupt step size (0, 1, 2, or 3). This value, defined as ΔQ, corresponds to the output of the FRBS. A step size of 0 means that Q remains unchanged.

Identification procedure: The process of identification for the proposed FuzzyQ in the form of a flowchart is depicted in Fig. 2 and described subsequently. The value of Q is initialised to 2, which is the smallest value it can take, and therefore $L = 4$. Tags with SC = 0 transmit their ID while the rest of them wait for further commands from the reader. Next, the reader sends the corresponding query (Qc, QA, or QR) and updates the counters *nc* and *ni* according to the tags' responses. If the reader detects a collision, *nc* is increased by one; if no tag responds, *ni* is increased by one; and otherwise, both counters remain unchanged. At this point, if the current slot is a *check slot*, ΔQ is obtained from the FRBS. Next, Q is increased by ΔQ if $nc > ni$, and decreased by the same factor otherwise. Finally, the resulting Q is rounded. If the current slot is not a *check slot*, the identification process will continue with the following slot.

Table 1: Performance comparison of FuzzyQ in terms of SE and IT

		SE		IT	
		CP = 2	CP = 9	CP = 2	CP = 9
Tag population	64	0.289	0.297	0.450	0.465
	128	0.302	0.312	0.879	0.891
	512	0.305	0.328	3.555	3.535
	1024	0.306	0.335	7.087	6.972

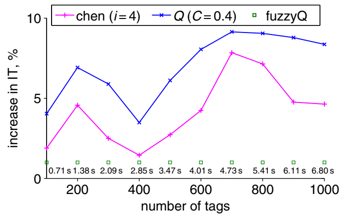

Fig. 4 *Improvement introduced by FuzzyQ in the IT*

Two extra considerations must be taken into account. When evaluating a *check slot*, a new frame is started only if the newly obtained Q differs from the current value. If this condition is not satisfied, the identification process will move to the next slot. Additionally, when the reader reaches the last slot of the frame, ΔQ is computed again in order to obtain the size of the next frame.

Simulation results: This section presents the results of the simulation experiments using MATLAB R2013a. The simulation uses a scenario with one reader and a varying number of tags, n, from 100 to 1000 tags, with a step size of 100. The tags are uniformly distributed and an ideal channel is assumed for the experiment [2]. The simulation responses are averaged over 1000 iterations for accuracy in the results. It is assumed that the identification procedure ends when all tags have been identified.

To analyse the performance of the proposed protocol, three main parameters are analysed in this section:

(i) *Slot efficiency (SE)*: The ratio between the number of tags and the number of time slots required to identify them.
(ii) *IT*: The total time employed by the reader to successfully identify all tags in a set.
(iii) *SF*: The fraction of QR commands in relation to the total number of commands and the number of examinations, defined by: SF = [*t*QR/(*t*QR + *t*QA)]/*t*exams

where *t*QA and *t*QR are the total number of QA and QR, respectively, sent by the reader during a complete identification round; and *t*exams is the number of *check slots* examined in the same round.

For all the presented simulations, the reader's and tag's command length is set according to the standard [1], with an ID of 96 bits. Moreover, in order to compute IT, a reader data rate of 128 kbit/s and a tag data rate of 47.4 kbit/s were employed.

SF provides information about the rate of introducing new frames. The parameter *t*exams relativises this factor to the number of attempts made to begin a frame. It is also important to note here that the slot duration employed to start a new frame (equal to *t*QA) is higher than the duration applied to decrement the tag's counter SC (equal to *t*QR). Analysing more in depth SF, on the one hand, the numerator is desired to be a maximum, since the length of QA is higher than the length of QR, and a lower number of reader-transmitted bits will lower IT. On the other hand, *t*exams is desired to be a minimum, contributing to the decrease of IT. As a result, SF is desired to be a maximum.

First, the value of CP must be selected so that it maximises the protocol's performance. Thereupon, SF is computed for a range of CP varying from 2 to 10. The value CP = 1 has not been considered because it involves just one examination of the frame size, whereas the rest of the values of CP might require up to two examinations (the first at *check slot* and the second at the end of the frame to determine the size of the next frame). The results are shown in Fig. 3*a*.

Fig. 3*a* shows two relative maxima at CP = 2 and 9. Therefore, in order to establish which one FuzzyQ must employ, SE and IT are analysed for both of these values of CP, on five different tag sets. Table 1 shows the simulation results.

As can be appreciated in Table 1, SE is higher for CP = 9 for all evaluated tag populations. Regarding IT, CP = 2 produces a higher SE factor for populations of 64 and 128 tags. However, most applications deal with sets larger than 128 tags. Consequently, CP = 9 is selected.

Once CP is set, the performance of the proposed protocol is evaluated in comparison with the algorithm presented in [3] with $i = 4$, Chen($i = 4$), and the Q-protocol with $C = 0.4$, $Q(C = 0.4)$ [1]. Considering the protocol Chen($i = 4$), the value of $i = 4$ has been chosen due to the fact that it results in the highest SE in [3]. First, the three protocols are compared regarding SF, as shown in Fig. 3*b*. FuzzyQ achieves a considerably higher value of SF than the other protocols for all tag sets evaluated. This is because FuzzyQ adapts to the population oscillations more effectively, lowering the rate of introducing new frames.

Finally, IT is evaluated. The IT is a highly relevant performance indicator, since it greatly influences the performance of the global RFID system. Fig. 4 shows the percentage increase in IT of the comparative strategies in relation to FuzzyQ. It can be appreciated that FuzzyQ presents an average improvement of 4.2% with respect to Chen($i = 4$) and a 7% average improvement with respect to the $Q(C = 0.4)$ protocol. The outcomes show that FuzzyQ lowers the IT needed by the other strategies. First, FuzzyQ reduces the proportion of QA in relation to the total number of queries and *t*exams. Secondly, by limiting the *check point* to one per frame, the number of examinations is reduced and so is the total number of QAs. Finally, by setting ΔQ to a range of values of up to three units, the protocol employs fewer slots to reach an appropriate value of L. As a result, a lower IT is justified.

Conclusion: A novel protocol based on the standard EPC C1G2 has been presented for fast RFID tag identification. Simulated results suggest that FuzzyQ is a dextrous protocol, using an FRBS, and achieving a relatively low IT while providing competitive results in terms of SF. FuzzyQ achieves a 4.2% average improvement in IT in relation to the strategy Chen($i = 4$) and an average improvement of 7% with respect to the $Q(C = 0.4)$ protocol.

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One or more of the Figures in this Letter are available in colour online.

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