RFID reader-tag communication throughput analysis using Gen2 Q-algorithm frame adaptation scheme

Petar Šolić, Matko Šarić, and Maja Stella

***Abstract*—** Dynamic Frame Slotted ALOHA (DFSA) is widely used Medium Access Control (MAC) mechanism in Radio Frequency Identification (RFID) systems. In RFID DFSA, communication between RFID readers and tags is organized in the interrogation rounds contained of frames which are further divided into slots. Upon announcing the size of frame, RFID tags are randomly taking the spot, i.e. the slot of the given time frame and they respond back to the reader when that slot is being interrogated. DFSA throughput, defined as a ratio between the number of successfully read tags (one tag response in the slot) over the size of frame, is greatly influenced by the size of frame. Setting wrong frame size will increase total time for tags identification due to number of empty (none tag responded within the slot) and collision slots (multiple tag responded within the slot) occurred. In this paper we evaluate Q-algorithm frame size adaptation scheme proposed in RFID Gen2 standard along with 3 typical scenarios of Gen2 physical setup, which enables us to measure total time for tags identification. In addition the impact on choosing the initial frame size is studied.

***Keywords*—**ALOHA; Dynamic Frame Slotted ALOHA (DFSA), Gen2 throughput, tags/s.

I. INTRODUCTION

RFID technology, based on the wireless communication between tags and reader is the most popular technology used for items tracking, identification, business process automation and various industry applications, localization, robotic, etc [1-3]. Typical RFID system is contained of RFID reader, (controlled by the host computer) which communicates through its antennas to RFID tags. Regarding frequency bands, RFID technologies can be divided into Low Frequency (LF), and High Frequency (HF) used for near-field applications (depending on size of its antennas, up to 30 cm of reading range), and Ultra High Frequency (UHF) and microwave frequencies for far-field applications. More detailed preview of different tags performances are given in [4]. In addition, tags

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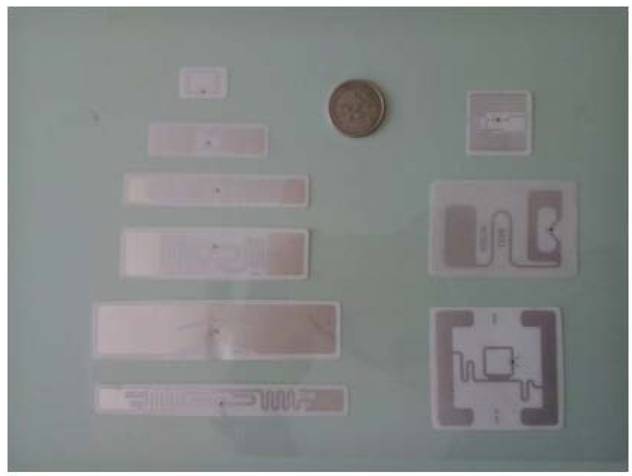

Fig. 1 RFID Gen2 tags, manufactured by Alien Inc.

can be with or without battery, which also regulates reading range as well as

its price. Gen2 RFID technology is the most promising technology in terms of the best price-performance ratio, and by presenting the enabling technology for Internet of Things (IoT) applications [5]. Gen2 tags could be read up to 10 meters away from the reader, they do not own battery and their price is about 0.1 USD. They are powered through radio waves transmitted by reader antenna. Examples of Gen2 tags are shown in Figure 1.

Due to small amount of energy received, to function properly, Gen2 tags cannot afford themselves energy expensive operations. Therefore, to communicate with the reader, some energy-efficient technique for multiple tag communication in the Medium Access Control (MAC) layer should be employed. In RFID systems widely used protocols for tag access control are Tree-based algorithms [6, 7] and ALOHA-based algorithms [8]. Due to its highest efficiency and simplicity, the most popular among suggested algorithms is Dynamic Frame Slotted ALOHA (DFSA) [9]. In Gen2 DFSA, communication is divided into rounds of interrogation contained of multiple frames further divided into the slots. At the beginning of the interrogation, reader is announcing the size of the initial frame, and tags are randomly taking the spot of the given frame. Afterwards, reader is interrogating a slot by slot until it reaches the end of the frame. From the slot perspective, what can happen is that none of the tags occupies it (empty slot), that one tag occupies it (successful slot) and that multiple tags occupy the slot (collision slot). Collision slot could not be properly decoded since the received signal is garbled by the sum of tag signals in the channel. Desirable scenario is one tag per slot which maximizes the throughput defined as the ratio of successfully decoded slots over the size of the time frame (sum of the number of collision, empty and successful slots). To maximize the throughput it is necessary to know the number of competing tags, and therefore set the size of DFSA frame to correct value. In this paper we evaluate the performance of Q-algorithm suggested as a frame adaptation scheme in Gen RFID system, with all significant details in order to compute mean time for tags identification. In addition we study the impact on the Q-algorithm initial frame size selection.

The paper is structured as follows. In the next section we describe usage of DFSA protocol in RFID systems, along with brief analysis of its throughput. In Section 3 we provide detailed analysis on timing of Gen2 protocol with description of DFSA frame adaptation scheme, called Q-algorithm. In Section 4 we provide simulation results of Gen2 process of tags identification using Q-algorithm for 3 different scenarios. In Section 5 we conclude our paper.

II. DFSA for ALOHA-based RFID Systems

In DFSA protocol (reader talks first (RTF) technology), reader-tag communication is divided into frames, further divided into time slots. At the beginning, reader announces the size of the time frame, which tags receive, decode and set themselves into the random position, i.e. slot, and respond back to the reader once their slot is interrogated. According to the type of the time slot, there are three possible scenarios:

- None of tags respond within the slot, which assumes slot to be empty
- One tag responds within the slot, which assumes that slot has been successfully read
- Multiple tags respond within the slot, which assumes collision slot which could not be properly read due to summation of tag signal on the reader antenna

Upon receiving the information of the slot type from the interrogated frame, reader should somehow know what to do next in terms of increasing/decreasing next frame size. Example of the interrogation rounds when the size of frame equals 4 is shown in Figure 2. What one actually wants is to reduce the number of empty and collision slot in order to increase number of successfully read slots, and thus make reader-tag communication more efficient.

A. Throughput Analysis

To increase the throughput of DFSA system, it is necessary to reduce the number of Collision and Empty slots, i.e. to increase the likelihood of detecting Successful slot. Only thing one can adapt is the frame size. For given frame size, providing lesser frame size would increase the probability of detecting collision slot, while providing bigger frame size would increase the number of empty slots. Both cases results in lower throughput. Therefore, the throughput is a function of

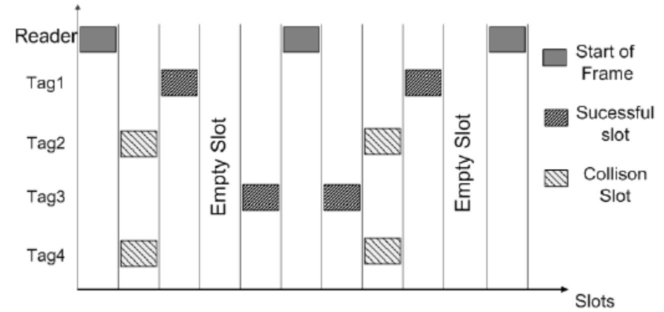

Fig. 2 Two reader-tag interrogation rounds, with four tags in the interrogation range

two variables: the frame size (L), and the number of tags (n), and can be defined as [10]:

$$U(\mathrm{n,p}) = \mathrm{np}(1-\mathrm{p})^{(n-1)} \tag{1}$$

where $p = 1/L$ stands for the probability of finding tag within a slot of the frame L. To find maximum throughput, one should find first derivative of (1) which equals zero, resulting in:

$$\frac{dU(\mathrm{n,p})}{dp} = \mathrm{n}(1-\mathrm{p})^{(n-2)}((1-\mathrm{p})\,\mathrm{p}(\mathrm{n}-1)) = 0 \tag{2}$$

which gives the maximum throughput when the number of tags n equals frame size L, and in that scenario, the maximum throughput is given as $U(\mathrm{n,p}) = 1/\mathrm{e} = 0.368$. Throughput for different frame sizes in DFSA is shown in Figure 3. As it can be concluded, the throughput of the system can be increased only if the number of tags is estimated correctly, and frame size set accordingly. There has been done a significant amount of work in order to estimate the tag number, such as [8–19], where none of the presented works does not evaluate Gen2 algorithms in means of standard physical setup of an Gen2

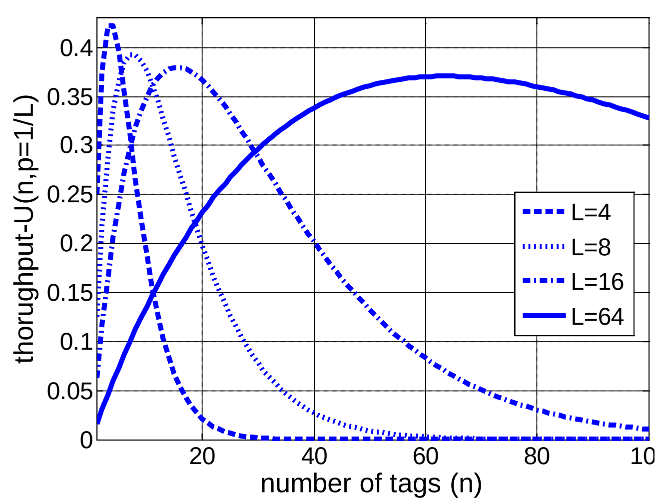

Fig. 3 DFSA Throughput for different frame sizes

RFID reader.

In the following section we provide concrete Gen2 DFSA implementation, including all significant details for its throughput analysis, along with the description and implementation of Q-algorithm given in Gen2.

III. DFSA GEN2 IMPLEMENTATION

Gen2 specifies protocol communication between reader and tags. When reader announces size of the frame ($L = 2^Q$) by broadcasting Q through *Query* command, tags take random spot in the frame using their built-in slot counters. Number initialized in the slot counter is random number in the range 0-$2^Q - 1$.

Once counters are initialized, reader begins the interrogation. Tag(s) having their slot counter set to 0, immediately respond back to the reader with their 16-bit random number (*RN16*). If reader successfully decodes tags *RN16* command, then reader acknowledge it using (*ACK*) command, which tag follow with their Electronic Product Code (*EPC*). *EPC* actually stands for the tag identifier which is used as a user-level code for item identification. Once *EPC* is successfully read, the slot is considered to be successful. If *RN16* or *EPC* is for some reason unsuccessfully decoded, reader transmits not acknowledged (*NAK*) command, and those tags are to be identified in future frames. If the slot is successful, reader issues *QRep* command. When tags decode it, they decrement their slot number by 1. Again, tags having slot set to 0 respond back to the reader. These steps are repeating until all slots get interrogated, i.e. there will be $2^Q - 1$ *QRep* commands. In the case of the empty slot, reader shall not wait the total time of *RN16*, due to request that tags should respond to the reader *QRep* in given time. Such communication protocol can be seen in Figure 4.

Interrogation in Gen2 is organized in rounds, which does not end until all tags get identified. When first frame of the first round finishes, only collision tags are moving to the next frame of the same round. Given round does not complete until there are collision slots. Once the round is complete, reader begins another interrogation round and identifies all tags again. Example of the interrogation round is shown in Figure 5.

However, all Gen2 commands are of different durations, where we in the next subsection provide analysis on duration for commands in Gen2 protocol that will allow us to compute total time for tags identification.

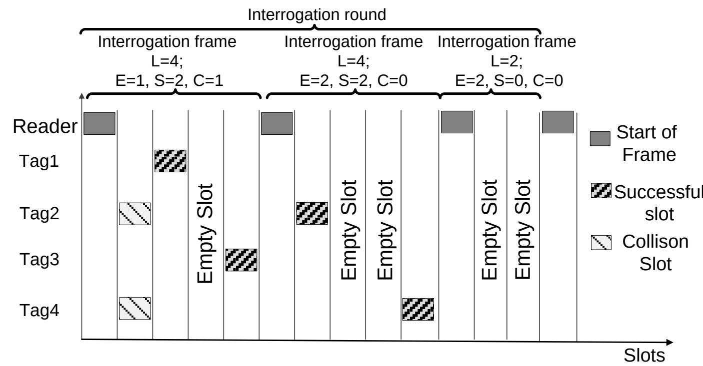

Fig. 5 Example of Gen2 reader-tag communication round consisted of 3 frames.

A. Timing in Gen2

Figure 6 gives all collision, empty and successful slots time details. *Query* command is consisted of reader-tag preamble (*PRT*) and 22 bits, where duration of each reader bit is denoted with Reader bith length (*Rbl*). *Rbl* is based on *Tari* value, $(2Tari+0.5Tari)/2 \le Rbl \le 3Tari/2$, while $6.25\mu s \le Tari \le 25\ \mu s$. *PRT* can be set to $12.5\times10^{-6}+Tari+2.5Tari+1.1TRCal$, where *TRcal* is tag-reader calibration symbol and equals $DR\times Tpri$, where *DR* stands for Division Ratio which can be set to 64/3 or 8. *DR* is used for defining tag-reader symbol rate, along with $Tpri=1/BLF$, and BLF stands for Backscatter Link Frequency (tag-reader response frequency), $40\text{kHz} \le BLF \le 640\text{kHz}$. Lower limit for *PRT* is $12.5\times10^{-6}+Tari+2.75Tari+3RTCal$, where *RTcal* is tag-reader calibration symbol ($1.5Tari \le RTcal \le 2Tari$). Duration of *Query* command is then:

$$T_{Query} = PRT + 22Rbl \tag{3}$$

ACK command is consisted of Time Frame Sync ($12.5\times10^{-6}+Tari+2.5Tari \le TFS \le 12.5\times10^{-6}+Tari+3Tari$) and 18 *Rbl* bits. Duration of *ACK* command RFID is then:

$$T_{ACK} = TFS + 18Rbl \tag{4}$$

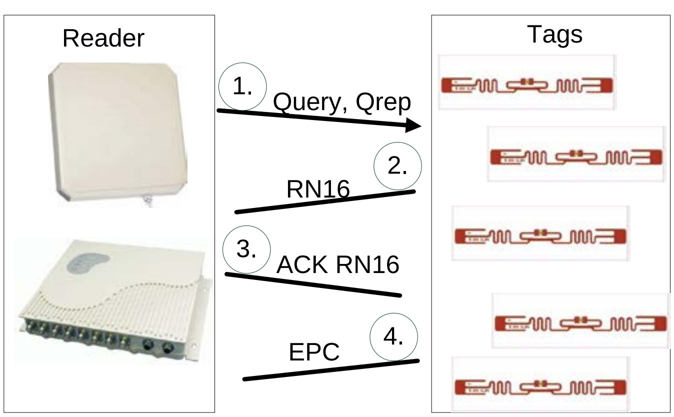

Fig. 4 Gen2 reader-tag communication model

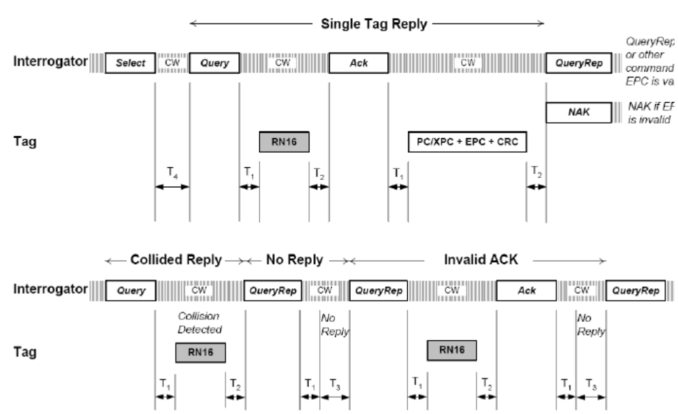

Fig. 6 Timing details for each slot type in Gen2

QRep command is contained of *TFS* and 4 *Rbl* bits, i.e. its duration is:

$$T_{Qrep} = TFS + 4Rbl \quad (5)$$

Time *T1* is in between max(*RTcal*,10*Tpri*)×(1-0.1)-(2×(10^{-6}), and (*RTcal*,10*Tpri*)×(1-0.1)+(2×(10^{-6}), while time *T2* is in between 3*Tpri* and 20*Tpri*. Time *T3* is given by minimum of 0.1*Tpri*, however this cannot be easily implemented in practice, due to tag response offset, and more sophisticated readers. Further, *M* denotes the number of Miller subcarrier cycles in tag response, which could be set to 1 (FM0-code), 2, 4 and 8. *TRext* value 1 ($TRext_1$=4) or 0 ($TRext_0$=16) denotes the presence or absence of pilot tone. Using given values, duration of RN16 command is:

$$T_{RN16} = \frac{TRext_i \times M}{BLF} + \frac{12M}{BLF} + \frac{2M}{BLF} \quad (6)$$

where last bit, i.e. 17th bit is dummy. Further, duration of *EPC* command is:

$$T_{EPC} = \frac{TRext_i \times M}{BLF} + \frac{12M}{BLF} + \frac{2M \times (16 + 96 + 17)}{BLF} \quad (7)$$

Therefore, duration of empty slot is given by:

$$T_E = T_{Qrep} + T1 + T3 \quad (8)$$

duration of collision slot is:

$$T_C = T_{Qrep} + T1 + T_{RN16} + T2 \quad (9)$$

and the successful slot:

$$T_S = T_{Qrep} + T1 + T_{RN16} + T2 + T_{ACK} + T1 + T_{EPC} + T2 \quad (10)$$

Using equations (8, 9, and 10), throughput in terms of tags/s is then given with ratio of successfully read tags divided with the duration of the frame:

$$U_t = \frac{N_S}{T_E N_E + T_C N_C + T_S N_S + T_{Query}} \quad (10)$$

Where N_S, N_E, N_C stands for the number of successful, empty and collision slots respectively.

B. Q-algorithm

Q-Algorithm suggested for usage to identify tags uses simple mechanism that is based on Q-learning algorithm [20]. It works in the way that system is learning from the previous evidence of number of Empty, Successful and Collision slots. Interrogation starts with some initial Q_{fp}, i.e. Q_{fp} = 4:0, and while interrogating slots, it learns in the following way: in the case of empty slot, Q_{fp} should be decreased for some C_Q, while

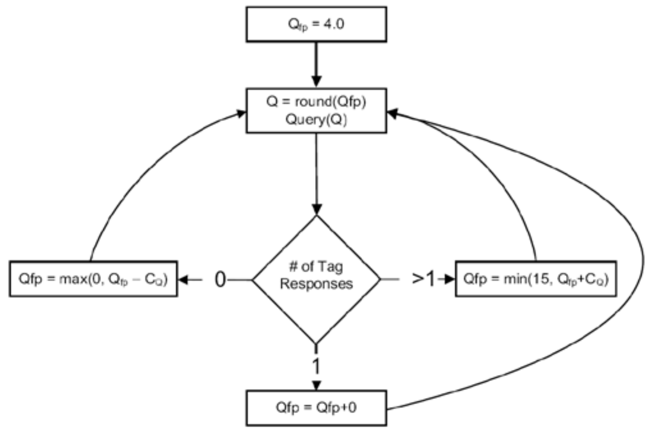

Fig. 7 Q-Selection algorithm suggested in [3], where 0:1≤ C_Q≤ 0:5

collision slot would increment Q_{fp} for value C_Q. However, proposed system is faulty since it does not specify the way how to choose constant 0:1≤ C_Q≤ 0:5. Once reader finishes interrogation of current time frame, it updates and broadcast new Q, as Q=round(Q_{fp}). Upon finish of the current interrogation round, Q is reset, i.e. system learns from the beginning. The state diagram of Q-algorithm is given in Figure 7.

IV. Simulation Results

Performance of Q-algorithm for all C_Q values is presented in

	Scenario1	Scenario2	Scenario3
Tari	25μs	16μs	6.25μs
RTCal	2Tari=50μs	Tari+0.75Tari =28μs	Tari+0.5Tari =9.375μs
BLF	40kHz	340kHz	640kHz
T1	27ms	29.412μs	12.063μs
T2	50ms	29.412μs	4.6875μs
TRext	0	0	0
M	8	4	1
T_{RN16}	12.4ms	552.94μs	96.875μs
T_{EPC}	57.2ms	3.2ms	446.88μs
T3	12.4ms	184.31μs	0.15625μs
PRT	0.2625ms	128.5μs	48.125μs
TFS	0.1125ms	72.5μs	34.375μs
Rbl	37.5μs	22μs	7.8125μs
T_{Query}	1.1ms	612.5μs	220μs
T_{ACK}	875μs	468.5μs	175μs
T_{QRep}	265μs	160.5μs	65.625μs
T_S	72.2ms	4.5ms	817.88μs
T_C	13.4ms	772.26μs	179.25μs
T_E	12.9ms	374.23μs	77.844μs

Tab. 1 Gen2 reader-tag interrogation parameters

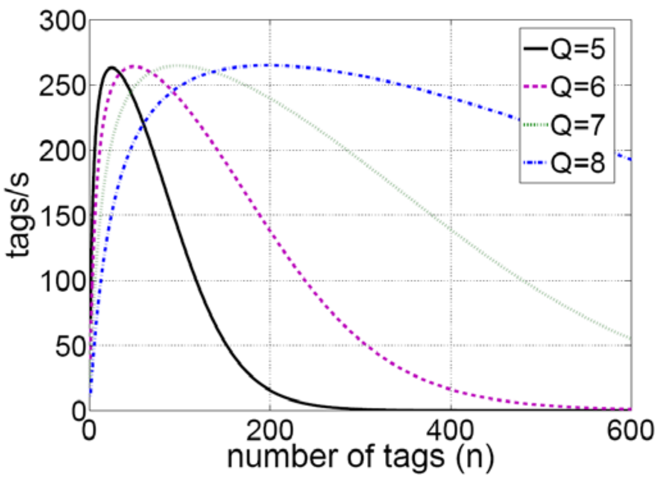

Fig. 8 Influence of choosing Q for tag reading in

the way to retrieve total time required to identify tags in Gen2 process of identification. Therefore, we have simulated tags identification through Monte Carlo simulations of 10000 rounds of identification for each C_Q where number of tags where randomly taking positions in the frame, and Q-algorithm was adapting the frame size accordingly. Number of tags in the experiment was varied between 1 and 250.

All simulations are conducted in the for the channel that is error free. Experiments were conducted for 3 Scenarios, given in Table 1. Scenario 1 is the lowest throughput scenario, which maximizes probability that tags responses will be successfully detected. Scenario 2 describes interrogation parameters with mean interval parameters of interrogation, while scenario 3 gives the highest Gen2 tag reading throughput.

Throughput example and impact on Q-usage of Gen2 protocol for the Scenario2 is shown in Figure 8. The impact of choosing correct frame size become more important when the error channel is applied. Therefore it can be concluded that choosing correct frame size is an critical factor in tag identification time.

While simulating Q-algorithm, we noticed that some scenarios can yield an error where the number of tags to be identified is ≥ 2, and Q-algorithm gives $Q \leq 0$. To avoid those scenarios we have limited Q, for C_Q, when resulting $Q \leq x$. In those scenarios Q should be set to the initial value. Values of x for different C_Q are given in Table 2.

A tag identification time for all three scenarios is provided in Figures 9, 10, and 11 when the initial Q=4. As it can be concluded from simulation results, C_Q = 0:3 provides the best option, which provides the most stable results.

C_Q	x
0.1	2.49
0.2	1.49
0.3	0
0.4	0
0.5	0

Tab. 2 Limitation of frame size to avoid estimate error

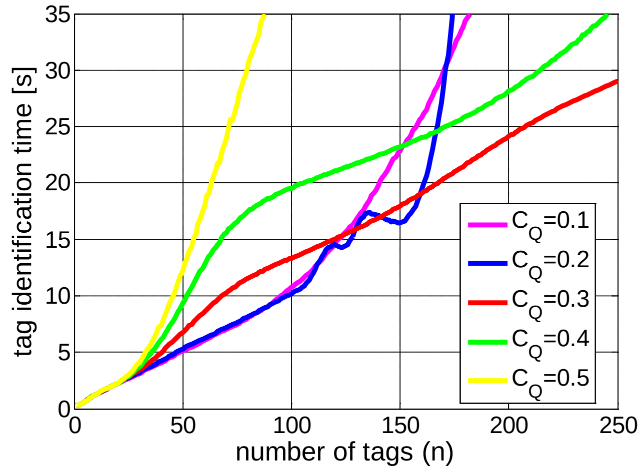

Fig. 9 Mean tag identification time for Scenario1

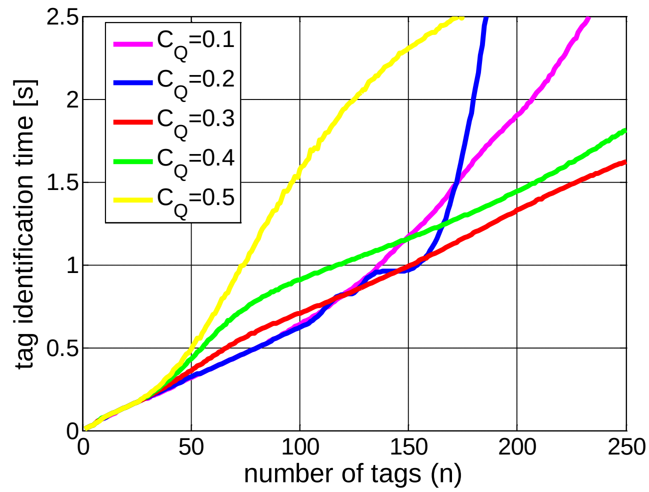

Fig. 10 Mean tag identification time for Scenario2

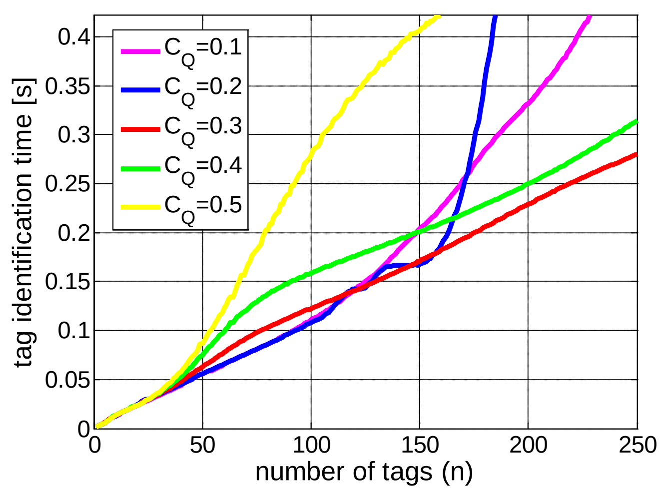

Fig. 10 Mean tag identification time for Scenario3

However, the impact on the throughput is great influenced by the initial frame size. Larger one will better suit higher number of tags due to reduced collisions, but at the same time it will have bad influence on the throughput for lower number of tags due to large number of empty slots occurred. In this section we analyze the impact of the initial frame size on the total tag identification time.

Since Q-algorithm is not based on the exact tag estimate, it is important to see its behavior in different initial frame sizes, and acquire performances knowledge and possible scenarios that could yield an error where the loop of identification could not be closed with given Q. For test purposes we used three initial scenarios of tag identification (based on Scenario2 timing), where initial Q was set to 5, and 6. Behavior of Q-algorithm can be seen in Figures 11 and 12. As it can be compared from the simulation results, each initial frame size has its optimal C_Q which minimizes total tag identification time. This brings to the further instability of the Q-algorithm. For different initial frame sizes it provides different tag identification time for different C_Q. Moreover, in author opinion the quality of Q-algorithm will be further reduced when considering realistic channel error scheme, and when considering all of it together, Q-algorithm provides low quality estimation, where some of the related works in the tags estimate should be employed.

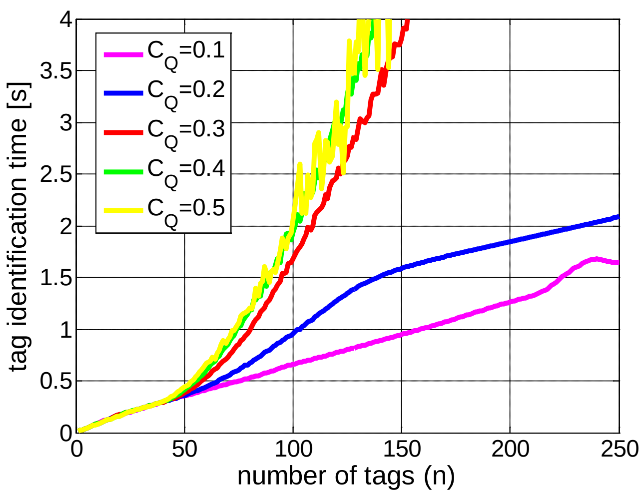

Fig. 11 Tag identification time for initial Q=5

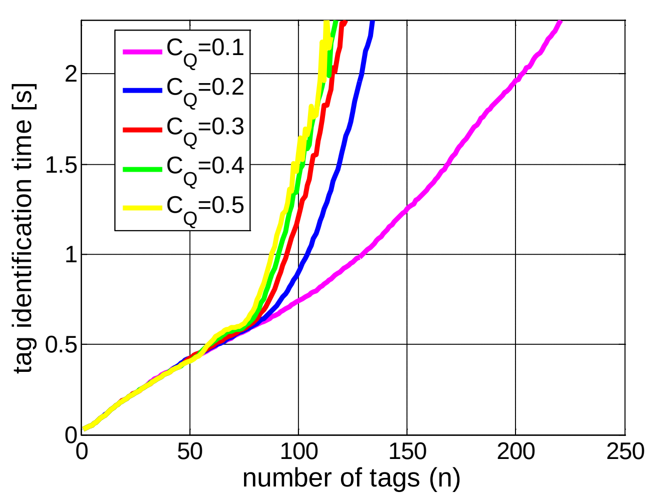

Fig. 11 Tag identification time for initial Q=6

V. Conclusion

In this paper we have analyzed throughput of Gen2 protocol when number of tags and tag interrogation parameter changes. From presented results it can be seen that usage of C_Q is critical factor when considering the throughput of Gen2 reader-tag communication. Results show instability of Q-algorithm when choosing different initial Q for static C_Q value, and therefore some other frame size technique for frame size adaption should be employed. Future work will include implementation of other algorithms for frame size adaptation, and its comparison with Q-algorithm, as well as the implementation and evaluation on Software Defined Radio (SDR) application [21], as done in [14].

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