Linearized Combinatorial Model for Optimal Frame Selection in Gen2 RFID System

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***Abstract*—Radio Frequency Identification (RFID) technology become an important tool for items identification and tracking. In this paper we observe RFID Gen2 communication protocol between the RFID reader and the low-cost battery free passive RFID tags. To establish communication between the reader and tags, Gen2 uses Dynamic Frame Slotted ALOHA (DFSA) Medium Access Control (MAC) layer protocol with Q-Selection algorithm for frame size adaptation. DFSA constraints of Gen2 RFID reader-tag communication may become an issue in the fast identification of all tags in the interrogation area. To identify all tags as soon as possible, DFSA frame size should be selected properly so its throughput is maximized, and that can be achieved only if one can estimate number of interrogated tags correctly. In this paper we present Linearized Combinatorial Model (LCM) algorithm for the optimal frame size adaptation. Developed scheme is implemented and tested on Universal Radio Serial Peripheral 1 (USRP1) Gen2 reader application. Results analysis shows that our scheme outperforms Q-Selection algorithm.**

***Index Terms*—Gen2 RFID, Dynamic Frame Slotted ALOHA, Optimal Frame Size Selection**

I. Introduction

RFID technologies based on wireless communication between the reader and tags are today widely used for items identification and tracking. Regarding tags battery presence or absence, RFID technologies could be divided into battery free tags in passive, battery assisted passive (BAP) and battery powered active RFID technologies [1]. To communicate with the reader, passive tags use the reader energy both for powering them up and to transmit their commands back to the reader.

Due to passive tags low computational abilities it is necessary to use MAC scheme which is computationally low cost. Today's Gen2 RFID readers to communicate with tags use DFSA protocol [2]. In Gen2 DFSA, reader informs tags about the number of time slots which tags can take to send their information back to the reader. The number of time slots (frame size) should be set properly in order to decrease tags identification time, and thus maximize communication throughput. In Gen2, frame sizes are adapted using the Q-Selection algorithm [3].

In order to maximize DFSA reader-tag communication throughput, one needs to provide proper frame size for tags interrogation. Providing optimal frame size is based one the estimate of the number of interrogating tags correctly and setting the frame size accordingly. This paper uses the model of interrogating tags number estimation based on the authors previous research, which includes developed combinatorial model and given linear property [4]. To adapt the model for usage as frame adaption scheme, given combinatorial model should be reduced, since its calculations is time consuming and could not be used in real application. In this paper we present the reduced model named LCM, which is developed and tested on USRP1 Gen2 reader [5] as frame size adaptation scheme. Results presented shows that LCM outperforms Q-Selection algorithm.

The paper is structured as follows: Section II. provides DFSA analysis with the current state of affairs in the field of optimal frame size selection. Section III. gives the description of the LCM, with the algorithm for optimal frame size selection. In Section IV. we provide the measurement setup with the results comparison of Q-Selection and LCM algorithm. In Section V. we conclude our paper.

II. DFSA Analysis and Related Works

ALOHA protocol was developed as random medium access control protocol. Gen2 RFID system use modification of ALOHA protocol - DFSA. In DFSA protocol reader informs tags about the number of time slots they can take to respond to the reader. Tags take the random spot in the frame and respond when their slot is being interrogated. Regarding timeslot occupancy, there are three possible scenarios:

- None of the tags replies within the slot, which is considered as the Empty slot
- One tag replies within the slot, which is considered as the Successful slot
- More than one tag replies within the slot, which is considered as the Collision Slot

Example of the interrogation frames is given within the Figure 1.

Calculation of the DFSA system throughput is given with [6]:

$$E(p) = np(1-p)^{(n-1)} \tag{1}$$

where p is the probability of finding a tag within the slot of frame, given as $1/L$, where frame size is L and n represents total number of tags being interrogated. In order to find maximum throughput DFSA, we derive (1), which results in:

$$E'(p) = n(1-p)^{(n-2)}((1-p)p(n-1)) \tag{2}$$

Point of the maximum is obtained for $p = 1/n$, i.e. when number of tags equals frame size ($n = L$). In that case we obtain maximum throughput of DFSA given as $1/e = 0.368$.

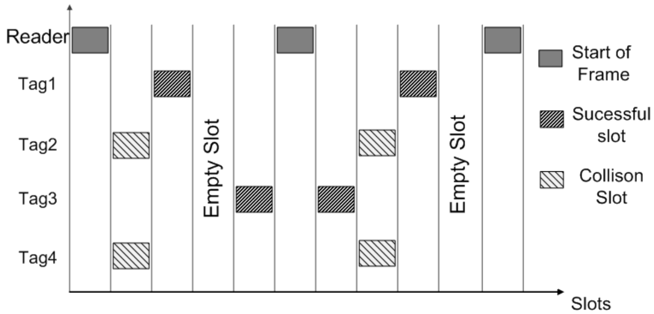

Fig. 1. Example of interrogation round with frame sizes equal to 4 and 4 tags in the interrogation area.

To set optimal frame size, one needs to estimate the number of tags in the reader's interrogation area and set the frame size to that value. Proper frame size selection reduces the number of both collision and empty slots with the goal of increasing system efficiency defined as

$$\text{Efficiency} = \frac{S}{E + S + C} \tag{3}$$

where S represents the number of Successful slots, E the number of Empty slots and C the number of Collision slots.

There have been many papers written about the optimization of DFSA protocol. In the following part we provide a few important analysis on the research topic.

A. Related Works

Schoute analysis [2] estimates the number of tags which need retransmission (all tags in collision slots) as $2.39C$, where C represents the number of collision slots within observed frame. Given retransmission scheme is provided when the number of tags within collision slot is Poisson distribution with integer mean value. Schoute analysis provides total efficiency of 42.6% for DFSA. However, given efficiency is only obtained when the number of tags requiring retransmission is exactly specified Poisson distribution.

Vogt proposal [7] uses Markov process chain for frame size adaptation, where optimal frame sizes for given estimation method are provided. Proposed scheme was implemented in Phillips I-code RFID systems [8]. To make the protocol more simple, frame sizes were reduced to the powers of 2, which according to [6], [9] lowers system throughput to 35%. Maximum throughput could be only achieved if the number of tags were set to the $round(log_2(n))$, where n represents number of tags within interrogation area.

Chen in his paper [10] provides accurate tag estimation method, where he consider distribution of tags within the frame as multinomial distribution. Probabilities of the slot occupancy are calculated through binomial distributions. However, Chen does not take in the consideration that number of tags within the interrogation area is limited source. Correct model is provided in [11], but it seems computationally expensive to implement in real RFID systems.

Floekermeier et al. in papers [9], [12] observe last z frames in order to update probability tables with idea to maximize probability of finding exact number of tags. Authors proposal includes calculations of exponential generating functions which could be time consuming for real time frame size adaptation.

Liu et al. in the paper [13] consider different slot duration time, which could increase the system efficiency. However, system lacks the tag estimation technique which could significantly reduce the time for tags detection.

B. Gen2 Protocol and its MAC background

RFID Reader starts the interrogation round with broadcasting $Query$ command. With $Query$ command, all relevant parameters for tags interrogation are being set. One of the fields in the $Query$ command is factor Q. When tags correctly demodulates and decodes $Query$ command, they set their slot counters to the random number between 0 and 2^Q-1. Tag(s) having its slot counter 0, respond back to the reader with 16 bit random number $RN16$. If reader decodes tags $RN16$ correctly, it sends Acknowledgement $ACKRN16$, to which tag replies with its Electronic Product Code (EPC). Next command reader sends is $QueryRepeat(QRep)$, which says to all tags to decrement their slot counters by 1. Again, tags having its slot counter 0 respond back to the reader. Number of $QRep$ commands which reader broadcast is 2^Q-1, with intense to decrease all possible slot counters and enable all tags to respond. If more than one tag responds at the observed timeslot with their RN16's it will be considered as the collision. However, if one tag signal is stronger than the others in collision, reader might be able to resolve the stronger one and Acknowledge it. This scenario is considered as the Capture Effect [7], which should be also considered for optimal frame size selection.

All of the given solutions in related works include the number of calculations to be done before setting frame size. Main advantage of Q-Selection protocol today widely used in Gen2 protocol is its simplicity with good performance results. Q-Selection protocol for its frame size selection uses the number of Successful, Empty and Collision slots. Its sequence diagram is given within the Figure 2 .

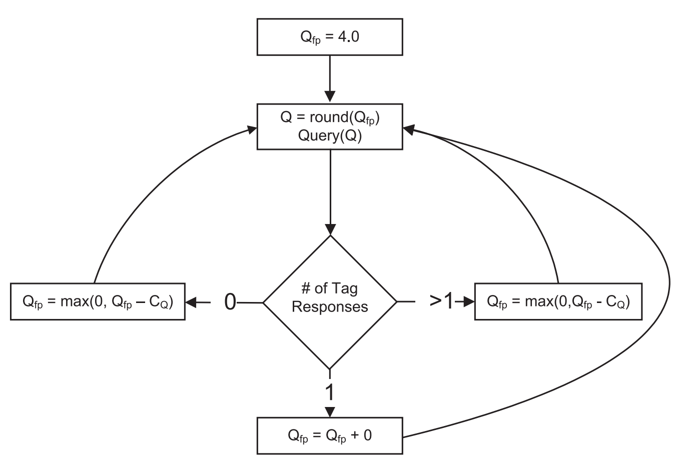

Fig. 2. Sequence diagram of the Q-Selection protocol [3].

Q-Selection has its main disadvantage of choosing its constant C_Q value, which can be $0.1 \le C_Q \le 0.5$, because there does not exist general rule for choosing C_Q value to be optimal. As it is reported by [14], C_Q value should be changed in the way when original Q is large, C_Q should be smaller than in scenarios when Q is small, where C_Q value should be larger. To avoid the problem of choosing C_Q, and to provide optimal frame selection method, we provide LCM algorithm described in the next section.

III. Linerized Combinatorial Model (LCM)

For the exact estimate of the number of tags we used 2 conclusions from authors previous work [4]. The first one is the linear property of given frame, where expected number of tags linearly depends on the number of successful slots for fixed number of collisions. Second conclusion we used is the combinatorial model developed, where

$$p(E,S,C \mid n) = \frac{\frac{S!}{(n-S)!}\left(e^x-(1+x)\right)^C \big|_{\frac{x^{(L-S)}}{(L-S)!}} \frac{L!}{E!S!C!}}{L^n} \tag{4}$$

E, S, C represent the number of Empty, Successful and Collision slots. L is the frame length given as $L = E+S+C$ and n is the number of tags. Part $\left(e^x-(1+x)\right)^C$ represents exponential generating function used to count all possible ways to distribute tags in collision slots.

In [4] authors proposed calculation of 4 characteristic points using to deriving equidistant lines (2^Q-1 of them) for each frame size. In this paper we provide the frame adaptation scheme full described with given combinatorial model, where all of the results are combined using linear property and thus providing correct linear model. Calculations of combinatorial model (4) is made using open source math tool SAGE (www.sagemath.org). Decision on the number of tags within interrogation area, i.e. its estimation is provided as:

$$\hat{n} = \underset{n}{\text{argmax}}\,\{p(E,S,C \mid n)\} \tag{5}$$

For the example, if we take frame size where $Q = 5$, $L = 2^Q = 32$, we obtain $p(E,S,C \mid n)$ distributions for different realizations of the frame (examples are depicted in the Figure 3).

To make linear model accurate we derived lines from the points obtained from combinatorial model for frames $L = 8$, $L = 16$ and $L = 32$. Example of linear behavior for $L = 16$ is shown in the Figure 4.

From the Figure 4 we notice that those lines are not equidistant, as suggested in the [4], so we interpolated the slopes (k) and $\hat{n}$-intercepts (l) for each $L = 8$, $L = 16$, $L = 32$. Best fitting for k's and l's for each frame size we got is using the 2nd order functions, which can be expressed as $f(C) = c_0^{(k)} + c_1^{(k)}C + c_2^{(k)}C^2$ for k and $f(C) = c_0^{(l)} + c_1^{(l)}C + c_2^{(l)}C^2$ for l. Interpolated functions can be seen in the Figures 5 and 6 and $c_i^{(k)}$, $c_i^{(l)}$ in the Table I.

To make k and l universal for every Q, we took the columns from the Table I and interpolated $c_i^{(k)}$ and $c_i^{(l)}$. The results are

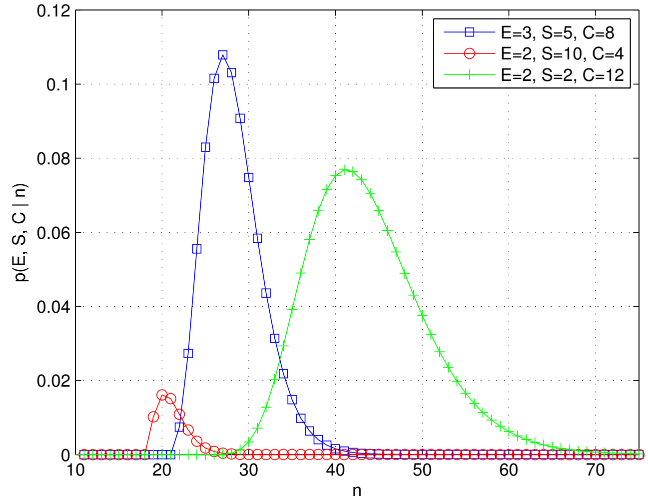

Fig. 3. Examples of $p(E,S,C \mid n)$ distributions, for different frame realizations if its size equals 16. We estimate number of tags as: $\hat{n} = \underset{n}{\text{argmax}}\,\{p(E,S,C \mid n)\}$

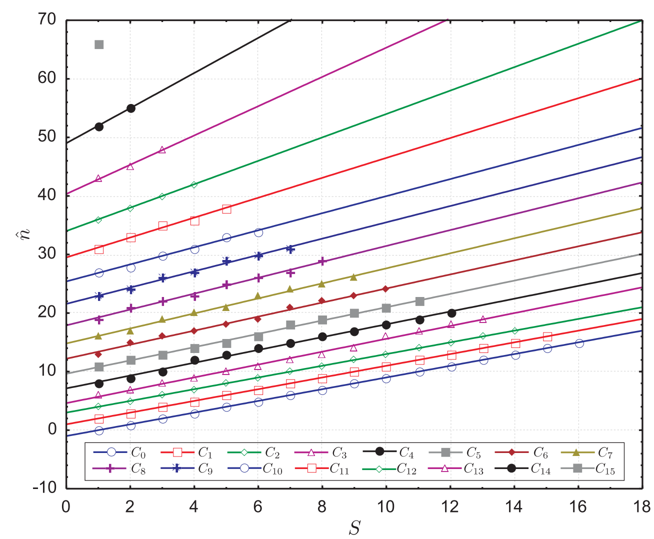

Fig. 4. Linear dependence of estimated number of tags ($\hat{n}$) and Successful (S), Collision slots (C). All points are obtained from calculations of given combinatorial model (4) given in [4].

TABLE I
Table of Coefficients $c_i^{(k)}$ and $c_i^{(l)}$.

L	$c_0^{(k)}$	$c_1^{(k)}$	$c_2^{(k)}$	$c_0^{(l)}$	$c_1^{(l)}$	$c_2^{(l)}$
32	1.4228	-0.1055	0.0057	3.7892	-0.03383	0.1182
16	1.2508	-0.1281	0.0152	-0.403	0.4503	0.1783
8	1.1429	-0.1607	0.0393	-1.7048	0.719	0.2524

depicted in the Figures 7 and 8. Obtaining universal k and l for every frame size, gives the universal algorithm for the optimal frame size selection given with the Algorithm 1.

Using given k and l, we estimate the number of tags $\hat{n}$ used to set new Q. Given algorithm is simple enough and could be used in real time calculations for optimal frame size selection.

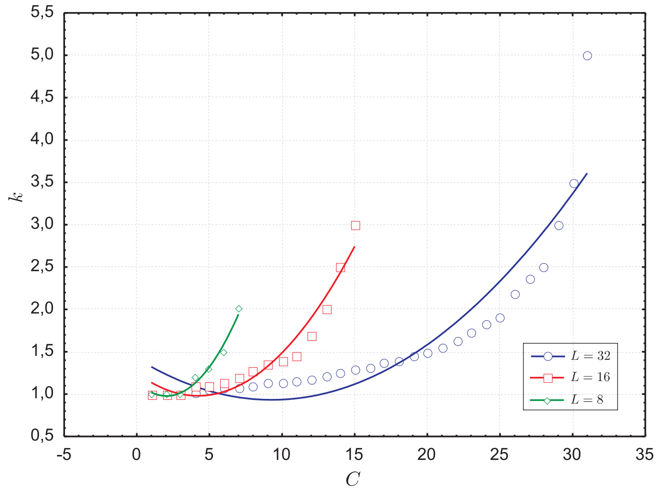

Fig. 5. Dependency of k for different number of C and L

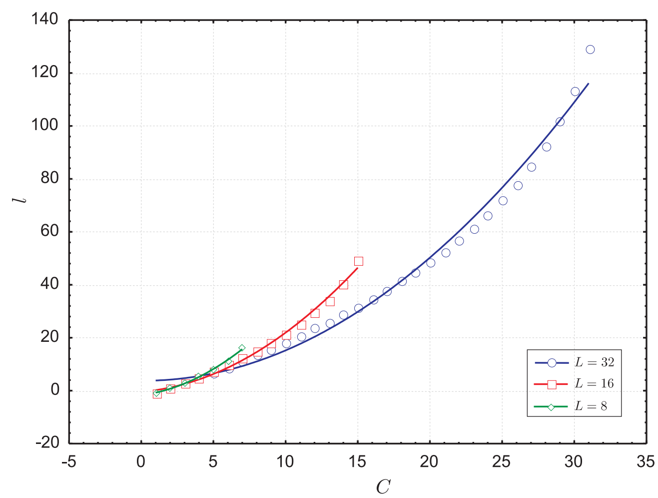

Fig. 6. Dependency of l for different number of C and L

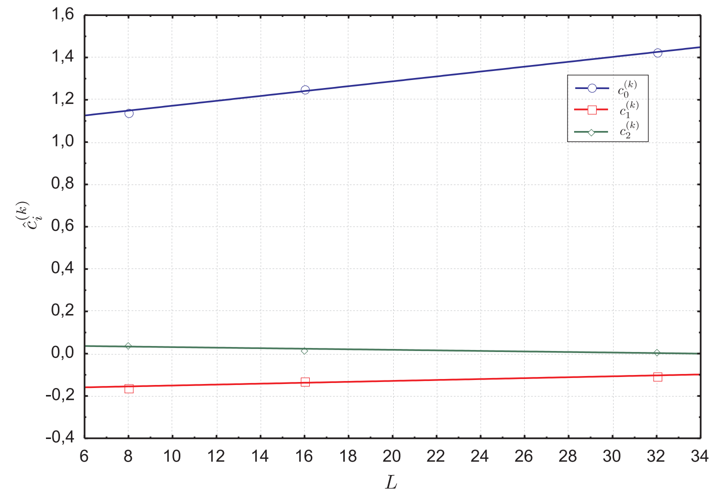

Fig. 7. Dependency of k coefficients for different L

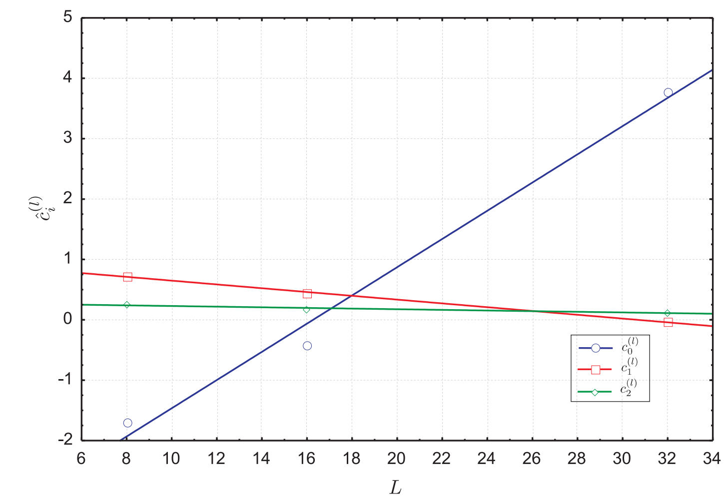

Fig. 8. Dependency of l coefficients for different L

IV. Measurement Setup and Performance Analysis

For described algorithm testing we have used Alien ALN-9640 tags and Gen2 reader [5] with its default settings including a few modifications given in the Table II. Testing setup includes USRP1 with 2 RFX900 daughterboards, one RFX900 daughterboard for receive and second transmitting RFX1800 daughterboard patched to RFX900 (gives maximum output power of 23dBm, adjustable by the amplitude level - see Table II). Reader uses 2 circularly polarized patch antennas with 6dBi gain. Tags were put together on 3 different boards, 0.8 - 1.5 meters away from the reader, and 1 meter above ground. On boards tags were separated 20 centimeters from each other, in order to decrease tag-to-tag interference [15]. Gen2 Reader central frequency used is 915MHz. During single measurements we provided static conditions, i.e. tag boards were not moving and all other movements in the room were minimized. System setup and its measuring block scheme is illustrated in Figures 9 and 10, respectively.

1: Calculate slope: $k = (1.0569 + 0.0115L) + (-0.172 + 0.0022L)C + (0.0441 - 0.0013L)C^2$
2: Calculate $\hat{n}$-intercept: $l = (-3.8 + 0.2336L) + (0.9633 - 0.0314L)C + (0.2825 - 0.0053L)C^2$
3: Calculate estimated number of tags: $\hat{n} = kS + l$
4: Calculate new Q_{fp}: $Q_{fp} = log_2(\hat{n})$
5: Calculate new Q: $Q = round(Q_{fp})$

Algorithm 1: LCM algorithm for optimal frame size selection. Algorithm input uses the L, C and S. As output it gives new Q to be broadcasted.

Figure 10 shows measuring system block diagram. For measurements we used Q-Selection, developed LCM and Optimal-Q based algorithm. Optimal-Q based algorithm sets Q parameter to the $round(log_2(n_e))$, where n_e represents exact number of tags being interrogated. As given in the Table II, Gen2 Reader setup was set to 100 reading cycles, i.e. 100 $PowerUp$ commands were set in which tags were interrogated through $Query$ and $QRep$ commands. Initial Q

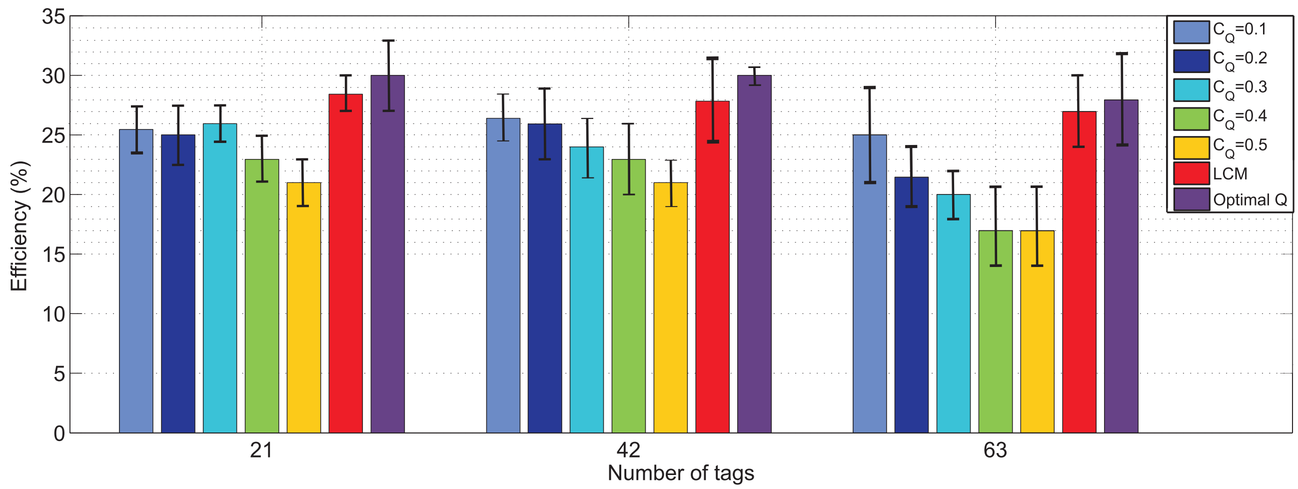

Fig. 11. DFSA efficiency calculated from (3) for Q-Selection, LCM and Optimal-Q based algorithms. Given uncertainty is provided for different reader-tags reading distances. Maximum throughput one theoretically can achieve is 36.8%.

TABLE II
USRP1 GEN2 READER [5] RUN PARAMETERS

Type	Variable	Value	File
int	CYCLE_TIMER_RATE	1000	rfid_global_vars.h
int	NUM_CYCLES	100	rfid_global_vars.h
bool	CHANGE_Q	*true*	rfid_global_vars.h
float	INIT_QFP	3	rfid_global_vars.h
int	amplitude	10000	gen2_reader.py
int	rx_gain	24	gen2_reader.py

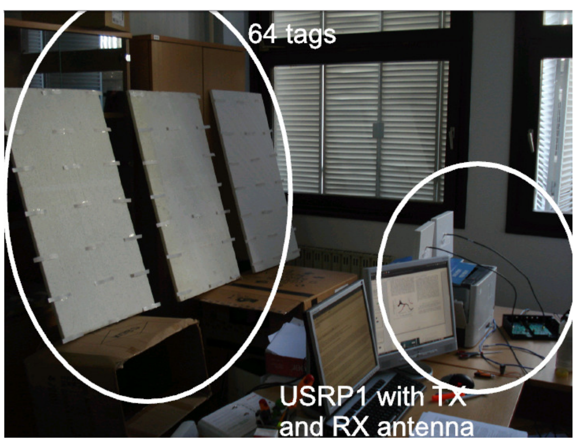

Fig. 9. System setup with standard office environment

is set to 3. Reader was reading tags first using Q-Selection then LCM and final Optimal-based Q algorithm on the sets of 21, 42 and 63 tags. Tests were repeated on 4 different distances between 0.8 and 1.5 meters. After all interrogation cycles are finished (in our case 100), Gen2 application can produce the output which logs all the communication between reader and tags. From the log one can obtain the number of $Query$ and $QRep$ commands which sum equals total number of slots $(E + S + C)$, and the number of correctly decoded $RN16$'s stands for the number of successful slots. To give performance results, we used the measure of system efficiency (3), and the results with its deviations (depending on distance between reader and tags) are depicted in the Figure

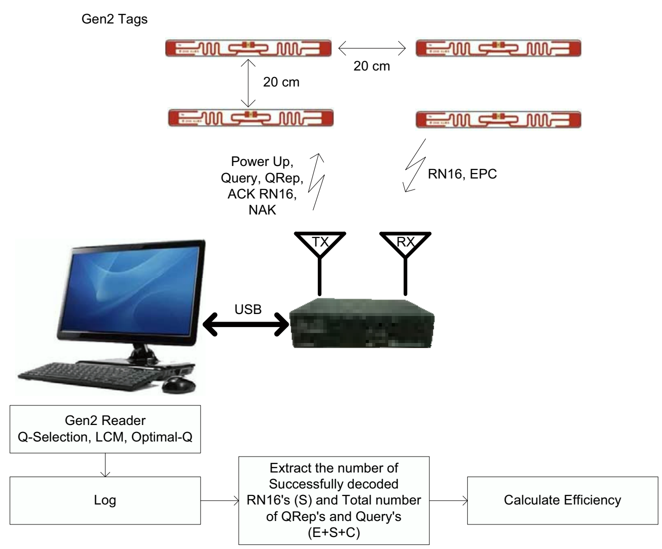

Fig. 10. Measuring system block scheme

11. The results show that LCM outperforms Q-Selection for every set of tags, and its performance is near optimal. It is important to notice that measuring the efficiency in the real conditions we provided includes all the radio-propagation behavior (including capturing), which is hard to incorporate in the theoretical models.

V. CONCLUSION

In this paper we provided the algorithm for optimal frame size selection within Gen2 RFID systems. The developed model is derived and implemented on USRP1 Gen2 RFID reader. Its performance results shows that LCM algorithm outperforms Q-Selection algorithm for every value of C_Q provided in Q-Selection algorithm. Another benefit in our proposal provides the universal rule for each frame size adaptation, where Q-Selection suffers from choosing the C_Q. Implementation of other authors proposals within Gen2 reader is considered for the future research, as well as more detailed analysis of throughput obtained from the results given in this paper. Moreover, for the future work we consider additional properties of Gen2 protocol as early frame cancelation, or setting the new frame size during the interrogation which could be used to increase the system throughput.

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