Linear model of Adapting Frame Size in DFSA of Passive GEN2 RFID systems

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Abstract: - Low costs of passive UHF RFID tags, as well as their simplicity makes them appropriate for the localization and tracking services in today's fast-moving, information rich trading networks. However, a few disadvantages of passive RFID technology performances, as a reading range of passive tags and high collision rate during RFID reader-tag communication, still needs quality of service improvements. In order to maintain passive technology cheap, but to improve the disadvantages, it is important for tags not to include any additional electronic circuitry, and to maximize the efficiency of the actual hardware. So, it is necessary to develop the optimal algorithms in order to maximize the communication efficiency.

In this paper we provide the analysis on MAC layer protocol of passive UHF-Gen 2 RFID standard. In the accordance with the standard, we provide the improvement for the frame size adaptation, which increases the throughput of RFID system and thus minimizes the time for tags identification. The algorithm for the improvement includes the estimate of the number of tags through the linear behavior model of number of Collisions (C), and Successful (S) slots within the frame. Estimated number of tags is used for adaptation of the frame size. For comparison, simulation results show that our approach provides better efficiency than Q-Selection algorithm from UHF-Class1-Gen 2 standard.

Key-Words: - Framed Slotted ALOHA, transmission control strategy, Q-selection Algorithm, RFID identification, Number of tags estimation

1. Introduction

RFID (Radio Frequency Identification) technologies are used today for building smart environments, different localization and tracking services, human habits monitoring, etc. Classic RFID system consists of RFID reader connected to computer, RFID antenna and RFID tags. Computer connected to RFID reader is controlling its functions. Reader through its ports sends signal radiated with RFID antenna in order to communicate with tags. According to the type of RFID tags we can divide RFID technologies into three groups [1]:

- Active RFID uses batteries for powering tags and its memory storage. Active RFID technology is more expensive but provides more robust, accurate and confident localization technique.
- Passive RFID tags do not have power supply. To initialize passive RFID tags for communication, tags use energy of electromagnetic waves radiated by RFID antenna, and thus through the modulation of backscattered radio waves [4] sends its memory content back to the reader [1,3]. Using passive technology we get more cost effective way of localization technique for mass use, because of simple electronic circuitry of UHF passive RFID tag, which lowers tags price to 0.10 $ [2]. However, disadvantages in reading range [7] or anti-collision control in communication channel still needs serious improvements for QoS improvement. Passive RFID system efficiency with backscattering and modulation problems was described in [8]. Communication between passive RFID tags and reader is depicted on the Figure 1.
- Semi-Active RFID uses batteries for powering tags memory storage, but data transmission is similar to passive technologies.

Our work assumes usage of passive UHF-Class1-Gen2, technology, standardized by EPCglobal [5] specifying identification, capturing and exchange of information protocols. EPCglobal organization specializes in the development of industry-driven standards for Electronic Product Code (EPC) network to support the use of RFID in today's fast-moving, information rich, trading networks.

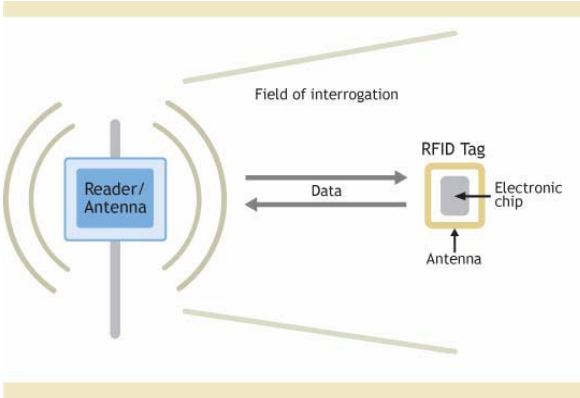

Fig. 1. – Illustration of passive RFID tag-reader communication

The architecture framework and the standards for identification, capturing and information exchange, which EPCglobal is specifying is depicted on the figure 2.

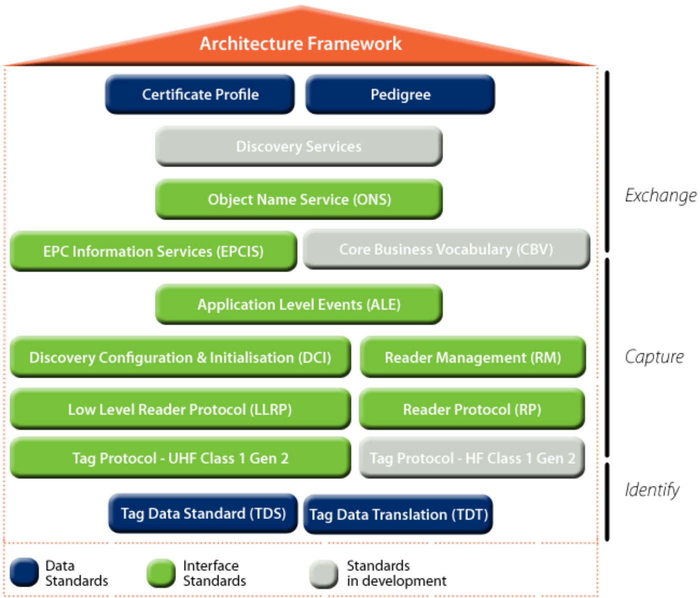

Fig. 2. EPCglobal architecture framework and standards for identification, capturing and exchange of information from EPC [5]

Within EPCglobal Framework, part described in Tag Protocol [6] is: Class 1 Generation 2 UHF Air Interface Protocol Standard "Gen 2" [6], commonly known as the "Gen 2" standard, as the upgrade of "Gen 1" standard. Gen 2 specifies communication protocols for tag identification on physical and data link level layers used for tags identification and capturing. Gen 2 defines the physical and logical requirements for passive-backscatter, RFID reader (Interrogator) Talks Firs (ITF) technology, and RFID systems operating in the 860-960 Mhz range.

Reading range of only a few meters in a free space of passive RFID systems and reducing the number of collisions while reader is interrogating the area where tags are, are the main lacks of passive UHF RFID systems.

In this paper we describe our novel anti-collision mechanism compatible with standard DFSA protocol. To be more specific, in this paper we described the problems of limits on the efficiency of the MAC (Medium Access Control) layer, as well as our proposal for the system efficiency maximization. Gen 2 Standard specifies Dynamic Framed Slotted ALOHA (DFSA) algorithm as the transmission control strategy and proposes Q-Selection Algorithm for dynamic adaption of frame length in order to maximize system efficiency. Framed Slotted ALOHA (FSA) without frame adaptation algorithm is depicted on figure 3. Reader initiates start of frame. Within the frame tags can transmit their data. To make algorithm efficient it is important to set optimal frame size, which length is equal to the number of tags [12] in order to achieve lower number of collisions (garbled slots) and empty slots during a frame cycle. To make the frame selection optimal, one needs to know number of tags within interrogation zone and set it as close as possible to that value. Since it is impossible to know dynamics of different interrogating environments, we have provided the results of monitoring the behavior of number of tags when the number of collisions and successful slots changes. Simulation is for the fixed frame size, and the results of the simulation are used for estimation of number of tags. Using the estimate we derive the optimal frame size. To see the system efficiency, we compare our simulation results with the results of Q-Selection Algorithm.

Rest of the paper is structured as follows: In section 2 we provide detail analysis on FSA algorithm and related works on the trace of several approaches deriving optimal frame size. Section 3 provides analysis and results of our approach on deriving optimal frame size.

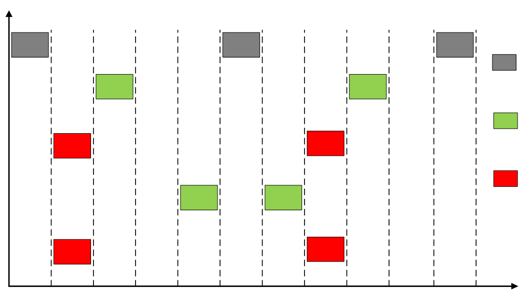

Fig. 3. Framed Slotted ALOHA with length of frame 4, and with 4 tags within of interrogation zone.

In section 4 we provide some concluding remarks and indications for the future work.

2. FSA Analysis and Related Works

Passive RFID technologies use a DFSA (Dynamic Framed Slotted ALOHA) protocol, which is based random access channel transmission. DFSA originated from an improvements of a few previous developed ALOHA based [13] transmission control schemes.

First one developed was the Pure ALOHA scheme, where stations send its data as soon as they receive the request for data transmission, or in RFID case, when tags get into interrogation range [1] [7] of RFID reader, which increases the number of collisions, because there was no mechanisms for stations to listen the medium and send data when channel is free.

To reduce number of collisions, but to stay within same concepts of random access transmission, and thus to reduce the time for a station communication, Slotted ALOHA (SA) was developed. It divides time into slots within stations can reply. This technique reduces the number of collisions by a half [1][8], but setting up the number of slots will be a problem if there is a number of tags within interrogation area. Problem is solved with Framed Slotted ALOHA (FSA) proposal, where time is divided into frames, and frames are divided into slots. FSA provides better results in collision ratio than other techniques, but it uses fixed frame size, where actually SA gives better results. In order to manage frame length Dynamic Framed Slotted ALOHA (DFSA) is used, where one can adapt frame length when necessary, in order to reduce collisions and slots where no station transmits.

Another approach in transmission control are Tree-Search Protocols [9], which according to [5] have greater complexity since each garbled timeslot generates a distinct sub-tree, whereas with dynamic frame length ALOHA all mobiles corresponding to any garbled timeslot of a frame are combined to one new backlog (the number of tags to retransmit) for the next frame. Framed slotted ALOHA has greater applicability since it takes into account the effects of noise and capturing. The implementation and research on the improvements on tree search algorithms were described in the works [10, 11].

Most commonly used scheme for Medium Access Control in passive UHF RFID technology is Dynamic Framed Slotted ALOHA protocol, where reader informs tags about number of slots (frame length) they can take. Protocol works in a way where RFID reader broadcasts *Q* using command *Query*, which tags receive and set up their counters as a random value from *0 to* 2^Q-1. When tags receive command *QueryREP*, they decrement their slot value by 1. First tag reaches the zero value sends its information back to the reader. Figure 3 illustrates Frame Slotted ALOHA where size of frame is 4. During RFID Reader-Tag communication there are three possible scenarios within the frame:

1. There is only 1 tag in a current slot reader is inventorying, which is the successful slot.
2. There is more than 1 tag in the current slot, which is the collision slot, because reader cannot resolve more than 1 tag signal. However, the standard [6] proposes resolving 1 signal if possible, but along with tag signal strength it may be not possible to do so.
3. There is no tag in a current slot, which is the empty slot in the frame.

Due to tags low computational abilities, there is nothing much we can do, except varying frame size to avoid number of empty and collision slots and increase efficiency of a system by increasing number of successful slots in the frame, as it is available in DFSA, so within the next subsection we provide the analysis on FSA, and what is necessary to do in order to maximize the through of the system.

2.1 Framed Slotted ALOHA analysis

To achieve maximum throughput in Framed Slotted ALOHA systems, we provide the analysis on the FSA protocol. The maximum throughput of FSA can be observed through the probability model of the frame. In the accordance with the work which addresses the analysis of the FSA protocol [5], we describe the throughput parameter, which is given with the:

$$E = \frac{P_S}{P_E + P_S + P_C} \qquad (1)$$

P_E denotes the probability that no tags respond during the slot, given with:

$$P_E = (1-p)^N \qquad (2)$$

Where p is the probability of finding a tag in a slot given as $1/L$, where L denotes the frame length. N is the number of tags within the interrogation area.

P_S is the probability that only one tag respond during the frame, which is given with the probability:

$$P_S = Np(1-p)^{N-1} \qquad (3)$$

P_C that is the probability that more than one tag respond during the slot, and it is then:

$$P_C = 1 - P_E - P_S \qquad (4)$$

Using relations (2-4) within the relation (1), we can see that throughput depends on the number of tags and the frame length:

$$E = \frac{P_S}{P_E + P_S + P_C} = Np(1-p)^{N-1}$$

In order to find the maximum throughput, i.e. probability p depending on the number of tags N, we ddifferentiate (1), which results in:

$$\frac{dE}{dp} = N(1-p)^{N-1} - Np(N-1)(1-p)^{N-2}$$

$$\frac{dE}{dp} = N(1-p)^{N-2}((1-p) - p(N-1))$$

$$\frac{dE}{dp} = 0 \rightarrow p^* = \frac{1}{N}$$

If we take *1/N* as a point of maximum value, i.e. frame length as a number of slots then we get:

$$E(p^*) = \frac{(1-\frac{1}{N})^N}{(1-\frac{1}{N})}$$

$$\lim_{N\to\infty}(1-\frac{1}{N}) = 1$$

$$\lim_{N\to\infty}(1-\frac{1}{N})^N = \frac{1}{e} \qquad (2)$$

$$\lim_{N\to\infty} E(p^*) = \frac{1}{e} = 0.368$$

Value of *0.368* is maximum efficiency of the FSA if number of tags equals frame length. However, to increase the system throughput, one needs to estimate the number of tags within the interrogation area.
To measure system quality, we use standard measure of System Efficiency given with:

$$System\ Efficiency = \frac{number\ of\ successful\ slots}{total\ number\ of\ slots} = \frac{N_S}{N_S + N_C + N_E} \qquad (3)$$

System Efficiency of a FSA system is depicted on figure 4. If we change frame size to be equal to the number of tags we can maximize System Efficiency. Another measure of system quality is the Collision Ratio:

$$Collision\ Ratio = \frac{number\ of\ collision\ slots}{total\ number\ of\ slots} = \frac{N_C}{N_S + N_C + N_E} \qquad (4)$$

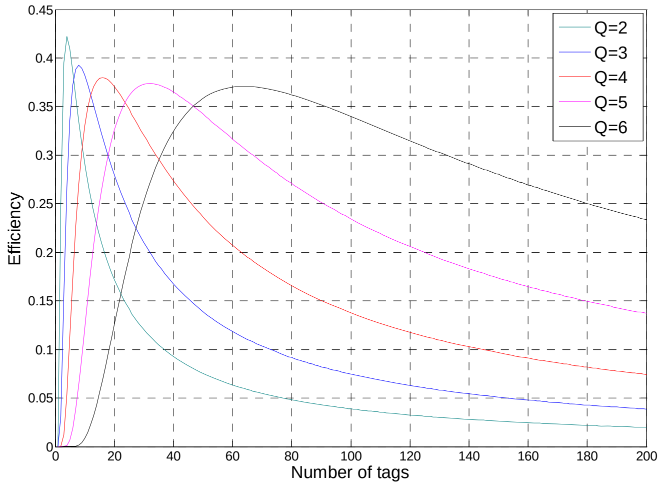

Fig. 4. Efficiency of the FSA for different frame lengths

In order to increase System Efficiency and to low Collision Ratio, frame length should be adapted using the DFSA protocol. However, it remains to make an optimal algorithm, where the selection of optimal frame size equals to number of tags, which maximizes the system efficiency. In the next subsection we provide detail analysis on Q-Selection Algorithm, as a standard in [6], as well as other author proposals.

2.1 Q-Selection algorithm and Related works

Adaption of the frame size in Q-Selection algorithm [6] is depicted on figure 5. Reader is sensing the environment by broadcasting *Q=4*, using the *Query* command. When tags demodulate and decode received value *Q*, they set their slot counters to random value from 0 to 2^Q-1. After the *Query* command, reader broadcasts *QueryRep* command. When tags demodulate the command, they decrement their slot counter by 1. *QueryRep* command is repeating during the interrogation round. First tag or tags reaching the 0 on their slot counter are replying within the frame. When the reader broadcasts 2^Q-1 *QueryRep* commands, interrogation round is over, and new *Query* command with different or same *Q* is broadcasted. Standard [6], specifies the *QueryRep* command, which can change the frame size during the frame interrogation, so the tags which are not inventoried, can take a position in the frame, which is higher or lower than one that is at that moment. To adapt the frame size, reader is counting the number of collision and empty slots during the frame interrogation. If empty slot occurs, Q for the next frame will be:

$$Q_{fp} = \max(0, Q_{fp} - C)$$

Or if collision slot occurs, Q for the next frame will be:

$$Q_{fp} = \min(15, Q_{fp} + C)$$

At the end of frame, reader broadcasts a new Q. Algorithm is repeating, where Q can be in range of *0-15*, and the constant value $0.1 \le C \le 0.5$ is chosen in the way to be small for high number of tags and large for low number of tags.

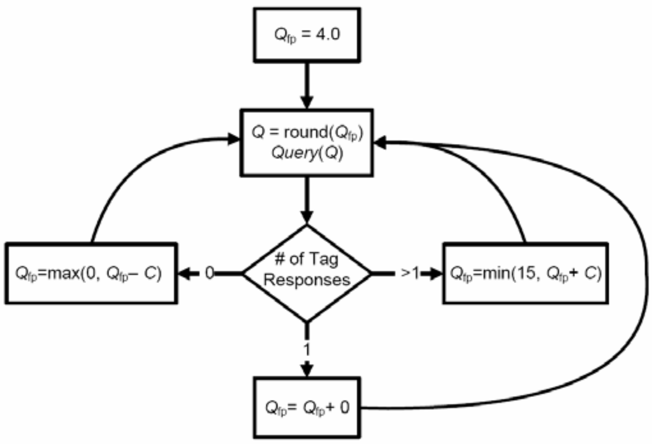

Fig. 5. Q-selection Algorithm sequence diagram from GEN2 [6] standard

However, the Q-Selection does not propose the exact C value. Due to unknown interrogating environment, Q-Selection may score lower system efficiency. Selecting optimal value C, in order to achieve better system efficiency, is depicted on the figure 6, where values of C's are obtained experimentally.

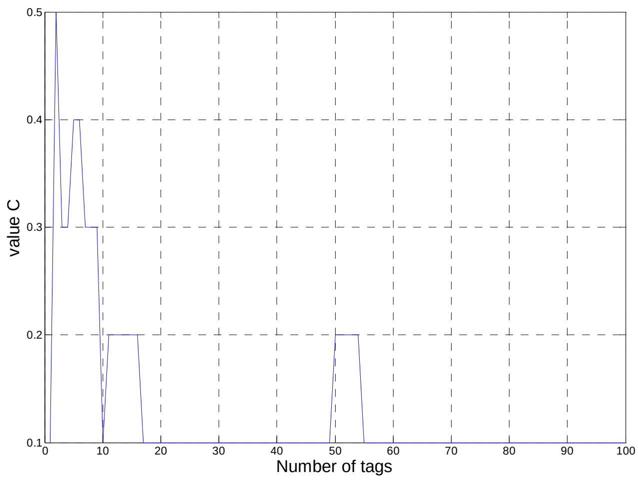

Fig. 6. Q-selection Algorithm optimal *C* values for different number of tags

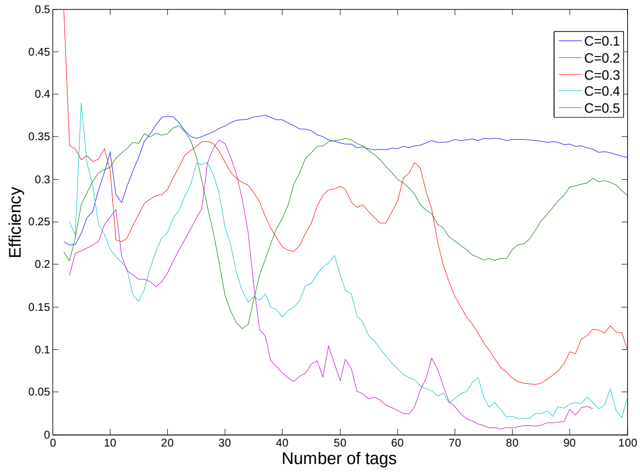

Fig. 7. Efficiency of Q-Selection Algorithm as Number of tags changes for different C value

Implementation and use of Q-selection is efficient and simple. Frame size should be adopted in order to minimize the number of garbled and empty slots, but also to increase number of successful slots in the frame. However, several authors proposed their solutions [11-22] for adapting the frame size in order to minimize number of garbled slots.

Authors in [17] use chebyshev's inequality as a minimal distance between expected value of distribution and random measuring result. Estimated number of tags is then given with the:

$$\xi(N, c_0, c_1, c_k) = \min_n \left\| \begin{pmatrix} a_0^{N,n} \\ a_1^{N,n} \\ a_{\ge 2}^{N,n} \end{pmatrix} - \begin{matrix} c_0 \\ c_1 \\ c_k \end{matrix} \right\|$$

Where values of c_0 is the read result of number of empty slots, c_1 is the read result of number of successful slots and c_k is the number of obtained collisions. Values of $a_0^{N,n}, a_1^{N,n}, a_{\ge 2}^{N,n}$ represent the expected number of empty, successful and collision slots obtained from binomial distribution, where the distribution:

$$B(n,r) = \binom{n}{r} \left(\frac{1}{N}\right)^r \left(1 - \frac{1}{N}\right)^{n-r}$$

depends on the frame size N and r, which is the number of tags within same slot, and n is the number of tags within interrogation area. However, the authors do not consider the number of tags as a limiting source.

Another approach [16] gives Bayesian estimation of number of tags from last z number of frames. The work is based on the Bayesian updating of the frame length whenever tags are departing or coming to the reader field of interrogation. Bayesian updating is given with the:

$$\Pr(N \mid y_{1:j}, z_{1:t}) = \alpha \Pr(N \mid y_{1:j-1}, z_{1:t}) \cdot \Pr(y_j \mid N, y_{1:j-1}, z_{1:t})$$

Where conditional probabilities should be calculated from probabilistic model, which is not easy to calculate in real time for each collision-empty-successful slot pairs. *N* represents number of tags and *y* represents evidence from the first slots in the current frame.

[14] assumes that there are only garbled slots and empty slots in the frame, and adaptation of the frame is modeled accordingly. The work described in [12] presents transmission control strategy by approximation of number of tags as a Poisson distribution. According to [12], maximum system efficiency what can be achieved is 42.6 %. By the author opinions, that can be achieved only if the distribution of tags is specific Poisson distribution.

Authors in [15] estimate number of tags as a collision rate for maximal throughput times number of collided slots a frame. Work [20] proposes setting of frame length as a

$$Q = ld \frac{N_s}{0.368}$$

which in high rate of tags provides better results than Q-Selection algorithm.

DFSA frame size adaption in [22] uses expected value of *2.39* for backlog estimation. Frame adaption is done only when the estimated tags number is *1.15* times greater than tags number in previous cycle.

In this paper we provide another approach which includes measuring number of collision and successful slots within fixed frame length. Obtained results shows linear behavior of changes, which extrapolation to each frame size shows better results than Q-Selection Algorithm and other approaches. In the next section we provide the algorithm of our approach as well as it results. To measure quality of different variants of DFSA, standard measures of System Efficiency and Collision ratio are used.

3. Lookup Matrix and Search Algorithm

For definition of measuring scenario several assumptions must be considered:

1. We use passive RFID technology, UHF-Class1-Gen2 tags
2. Reader talks first technology
3. Space of testing must be ideal, without interfering of other devices and reflection interference.
4. There is no early cancelation of the transmission during the frame, as it is done within work of several authors [13, 17].
5. There were no errors in the wireless channel during the identification procedure. That means that error due to propagation delay, path loss, and noise is ignored.
6. Due to tag random generators we consider that generation of random numbers have the uniform distribution.

Our improvement include estimation of total tag numbers $(\hat{N})$ within the interrogation zone and thus deriving Q as:

$$Q = \log_2(\hat{N})$$

Estimated total tag number is obtained experimentally.

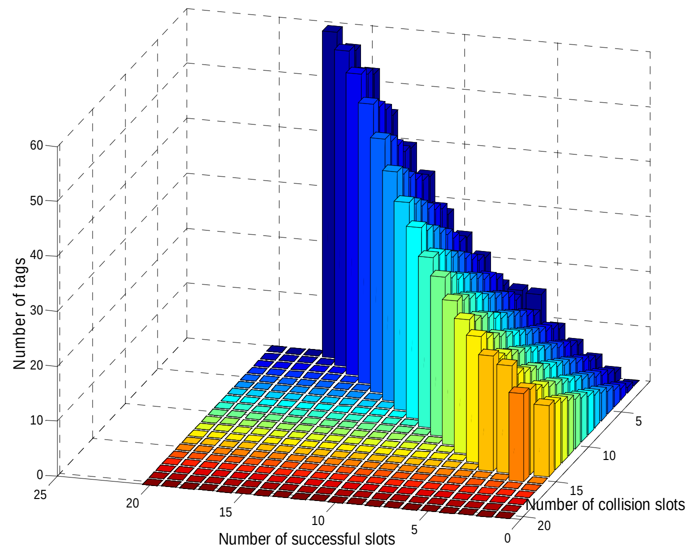

Fig. 8. Lookup matrix graph, with constraints on frame size, Q=4

If we take fixed frame length ($L=2^Q=16$) and $n=100000$ experiments of throwing $N=64$ "balls" (tags) into random frame spot we obtain Lookup matrix considering two variables, the number of collision slots and the number of successful slots, where the parameter is estimated number of tags. Lookup matrix provides estimated number of tags for all combinations of successful and collision slots in the frame. Value in the Lookup matrix is a mean value of realizations for each collision and successful slot pair. As a mean value we took position mean value of mode, as a more accurate representative. Maximum value what Lookup Search Algorithm can provide is the estimated *N* for *Q=7*, for all collision slots scenario, when frame size is *16*, while Q-Selection can provide maximum

$Q = round(16 \cdot 0.1) = 2$ for all collision slots scenario if we choose $C=0.1$ for a large number of tags. Value C can be higher, then we can estimate higher tag number, but also gain lower efficiency of the system, because of high number of empty slots, as it is depicted on figure 7.

For the Algorithm implementation we use the first frame with $Q=4$ for sensing the environment (finding pair of collision-successful slot number), and the size of the next frame is obtained from the LookUp matrix for resulting scenario of collision and successful slots. For the pair, number of tags is obtained from Lookup matrix and thus using $Q=round(log2(N))$ optimal frame size is derived. Figure 8 represents linear behavior of collision-successful slots changes results in the Lookup matrix (*Q=4, n=100000 experiments, N=64 tags*) when number of tags is increasing.

Results provided on figure 8 can be displayed in 2-dimensional space as a combination of collision slots and estimated tags number, where parameter is a number of successful slots.

The other way to display it is using number of successful slots and estimated number of tags, where parameter is a number of collision slots. Both variants are depicted on figures 9 and 10. If we consider figure 10 we can model the lines as depicted on figure 11 and extrapolate them to be usable in any frame length, as a lines which are equidistant within frame length of any size. We use minimum and maximum points and derive line through predefined points. Minimums and maximums are constrained with the frame size. Constraints meaning are that total number of tags cannot be larger than number of collisions and number of successful slots. Last line for $N_C=16$ actually represents a single point, but experiments showed that full collision scenario actually represents frame length of $2^7=128$, so we modeled it accordingly, as it is depicted on figure 11. With results obtained from Lookup matrix we generalize behavior for every frame length *1-32768*. Pair of minimum and maximum is derived for each collision slot scenario within the frame, and the proper value of number of tags is calculated. Experimentally obtained we derive all-collision scenario with Q value which is increased for value 3, i.e.

$$Q_{all\ collision} = Q_{last\ frame} + 3$$

Next frame length is adopted according to estimated $(\hat{N})$ as a $round(\log_2(\hat{N}))$.

Modeling of lines in this paper is obtained experimentally, but future work will include combinatorial model of theoretical thresholds for each collision-successful slot pair. To obtain the theoretical threshold, one needs to calculate and maximize probability distribution of tags within the frame for given number of successful, empty and collision slots. With theoretical thresholds one do not have to build the LookUp matrix, because the frame would be defined with 4 characteristic points per each frame of different lengths. It means that all collision scenario from the model will be the last line, and the first one is for 0 collisions and 0 successful slots with 0 collisions and 16 successful slots.

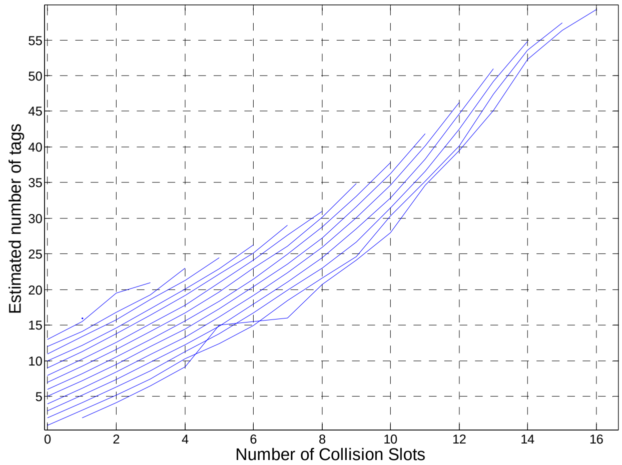

Fig. 9. Behavior of estimated number of tags if number of collision changes during a frame (Q=4). Parameter is number of successful slots (down-up 0-15)

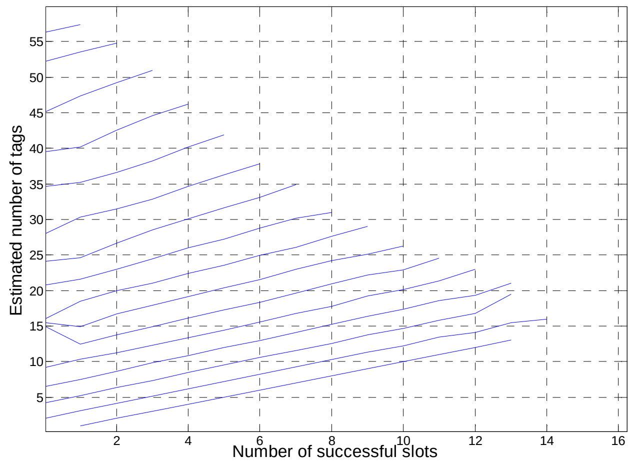

Fig. 10. Behavior of estimated number of tags if number of successful slots changes during a frame (Q=4). Parameter is number of collision slots (down-up 0-15). All collision scenario (last line) is the single point on estimated number axis

3.1 The Algorithm and performance analysis

The LookUp algorithm for optimal frame size selection is given as follows:

1. Broadcast single $Q=4$, for the environment sensing

2. Create the equidistant lines for given *Q*. All collision scenario sets the next frame length to the :

$$Q_{all\ collision} = Q_{last\ frame} + 3$$

3. Use the number of successful and collision slots to estimate the next *Q*, given with the $Q = round(\log_2(\hat{N}))$. Set the estimated $\hat{N}$ to the $\hat{N} = \hat{N} - S$, because the S slots are already read by the reader during the previous round of interrogation.
4. Iterate the steps 2 and 3 of given algorithm, while interrogation runs.

Using the extrapolated data from the developed model, implemented algorithm estimates frame length for every frame size. Extrapolation of the lines to the frame which length is set to 32 is depicted on the figure 12.

Starting value of *Q=4* is used like in the Q-Selection algorithm. *Q=4* is neither big nor small for the environment sensing. Validity of starting *Q=4* is depicted on the figure 13, where the system efficiency is actually near optimal value. Reducing the frame sizes to the powers of 2, actually lowers the system efficiency of DFSA to 35 % [13].

To make comparison with the Q-Selection algorithm, standard measures of system efficiency (3) is used, as well as collision ratio (4) as another result dimension, describing model parameters as the number of successful, collision or empty slots in a frame. System efficiency of both algorithms are depicted on the figure 13. Results show that LookUp algorithm provides better system efficiency in all cases, i.e. for each number of tags in interrogation area.

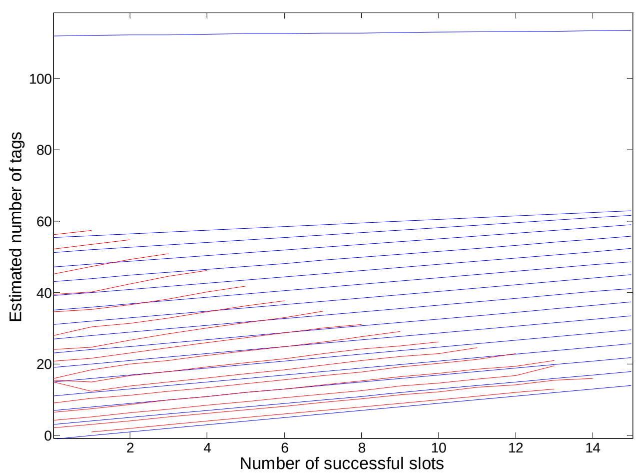

Fig. 11. Modeling of the lines from fig 10, as a linear model

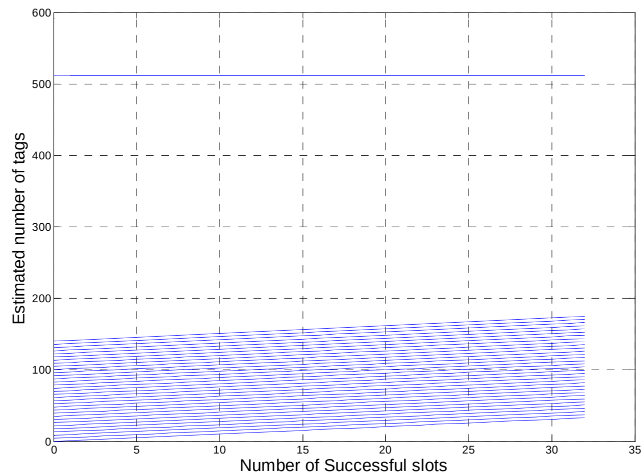

Fig. 12. Extrapolation of the lines to the frame which length is set to 32

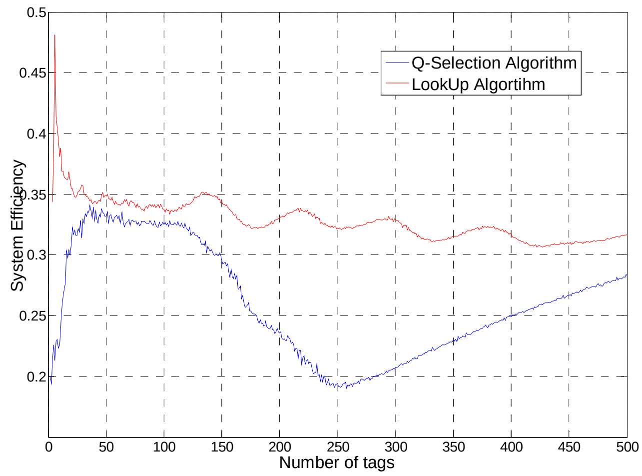

Fig. 13. Efficiency of Q-Selection and LookUp Algorithm

On Figure 14, collision ratio is depicted both for Q-Selection and Lookup Algorithm. Results for Q-Selection is for C=0.1, as best chosen C for high tag rate, as it is depicted on figure 7. With low collision ratio of Q-Selection algorithm, results of empty slots ratio is higher, because of lower efficiency than LookUp algorithm. It means that Q-Selection algorithm for higher tag ratio estimates larger frame size, and thus increases the number of empty slots. Authors in [10] provide mean collision ratio value of 0.25 for their algorithm approach; however our work lowers it on several segments as it is depicted on figure 14.

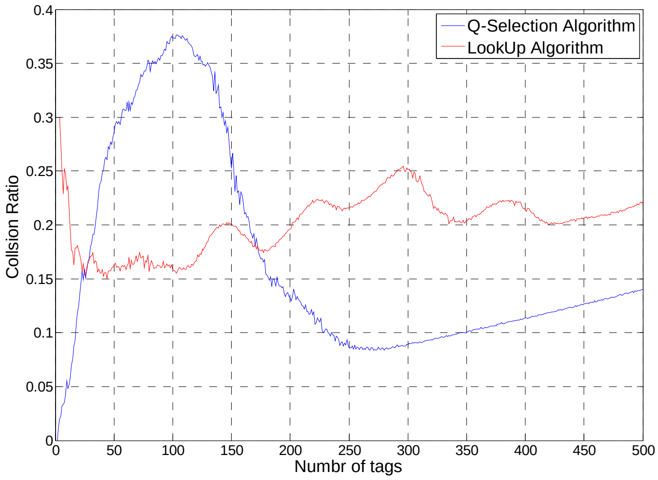

Fig. 14. Collision Ratio of Q-Selection and Lookup Algorithm

4. Conclusion and the Future work indications

In this work we presented the improvement for tag estimation number in the manner of more precise frame length definition and thus reducing tag identification time. Algorithm includes finding pair of collision and successful slots number in the LookUp matrix, which is the mean value of experiments realized for collision-successful pair and represents estimated tag number within interrogation zone. Using the estimated number of tags we derive optimal frame size as a $Q = \log_2(\hat{N})$.

Results obtained in the LookUp matrix, can be extrapolated as a equidistant lines within the frame of any size, thus deriving optimal *Q*. So it is not necessary to derive the LookUp matrix for each frame size, since the extrapolation provides System Efficiency near the maximum. Provided results show that our algorithm gives better System Efficiency results than standard Q-Selection Algorithm.

Future work will include combinatorial model of number of number of tags estimation and theoretical thresholds for collision-successful slot pair, since they are provided experimentally in this paper. To verify LookUp Algorithm approach authors will use A Flexible Software Radio RFID Reader, built using USRP Software Radio Platform in conjunction with GNU radio framework, developed by [23].

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