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Algorithm for Deriving Optimal Frame Size in Passive RFID UHF Class1-Gen2 Standard Using Combinatorial Model Boundaries

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MAC level efficiency constraints of the RFID Reader-Tag communication require proper frame size selection in order to achieve maximum throughput. To set optimal frame size, one needs to estimate the number of tags. Deriving optimal frame size results in reducing time for identification of large RFID tag populations, and thus increases throughput of RFID system.

In accordance with the standard Dynamic Framed Slotted ALOHA (DFSA) protocol, we propose model for frame size adaptation using number of collisions (C) and successful slots (S) within the frame length L. We found that expected number of tags N, linearly depends on S in the frame of length L, for fixed C. Proposed model for estimation of the number of tags can be described with 4 characteristic points, which can be calculated from proposed combinatorial model. Algorithm implementation in the first step estimates number of tags, and then in the second step, using the estimates, set the optimal frame size.

In order to compare proposed system performance with the other approaches, we use standard measures, System Efficiency and Collision Ratio. Simulation results show that our method provide better performance than the Q-selection algorithm, specified within the UHF-Class1-Gen2 standard.

Key words: Dynamic framed slotted ALOHA, Transmission control strategy, Q-selection algorithm, RFID identification, Tags estimation method (TEM)

Algoritam za definiranje optimalne duljine okvira u pasivnoj UHF Class1-GEN2 tehnologiji korištenjem ograničenja iz kombinatornog modela. Ograničenja MAC sloja u komunikaciji RFID čitač-tag zahtjevaju ispravno odabiranje veličine okvira s ciljem postizanja maksimalne propusnosti. Da bi se postavila optimalna duljina okvira, potrebno je procjeniti broj tagova koji se nalaze u području čitanja. Odabir optimalne duljine okvira rezultira skraćivanjem vremena za identifikaciju velikog broja RFID tagova, te povećanja propusnosti sustava.

U skladu s standardnim Dynamic Frame Slotted ALOHA (DFSA) protokolom, predlaže se model za adaptaciju duljine okvira korištenjem broja kolizijskih mjesta C i uspješno pročitanih mjesta S unutar okvira duljine L. Istraživanjem je zaključeno da očekivani broj tagova N linearno ovisi o S u okviru duljine L za fiksni C. Predstavljeni model za procjenu broja tagova se može opisati sa 4 karakteristične točke, koje se mogu izračunati iz predloženog kombinatornog modela. Implementacija algoritma u prvom koraku procjenjuje broj tagova, te u sljedećem koraku korištenjem procjene, postavlja optimalnu duljinu okvira.

Da bi usporedili rezultate sa drugim pristupima, koristimo standardne mjere efikasnosti sustava i omjera kolizija. Rezultati simulacije pokazuju da naša metoda omogućava bolje performanse nego Q-Selection Algoritam, specificiran u UHF-Class1-Gen2 standardu.

Ključne riječi: dynamic framed slotted ALOHA, strategije kontrole prijenosa, Q-selection algoritam, RFID identifikacija, procjena broja tagova (TEM)

1 INTRODUCTION

RFID (Radio Frequency Identification) technologies are recently being used for various identification schemes, animal tracking, building smart-homes, tagging products in stores, etc. RFID system consists of RFID tags and RFID reader connected to RFID antenna. Reader sends signals through its antenna and thus communicates with RFID tags. According to the type of RFID tags and the way how tags communicate with the reader, RFID technologies can be divided into 3 groups [1]:

1. Active RFID - Tags have their own power supply. Communication range between active RFID tags and reader is between 50 and 100 meters in free space.

Localization techniques using active RFID are more accurate. However, disadvantages of their robustness and price still make them inappropriate for all-type localization techniques. [2]

2. Passive RFID - Tags don't use power supply to power them self up. They use energy radiated from reader antenna and backscatter its memory content back to the reader. Prices of passive RFID tags are low and range within they can communicate with RFID reader is a few meters in free space. They are sometimes referenced as modern bar codes.

3. Semi-Active RFID - Tags use power supply for powering only tags memory storage. Communication through backscattering is same as in passive RFID technology. Semi-active technology is more expensive and robust than passive RFID.

Miniaturization concepts which are main advantage of RFID technologies overall, brings with themselves new problems for system designers. Passive RFID tags are cheap and small, but their computational abilities are low, since they include simple electronics. So, within those limits it is necessary to develop optimal algorithms in order to maximize reader-tags communication efficiency. To maximize efficiency it is important to optimize backscattering [3] [4] [5] on the physical layer and to develop efficient Medium Access Control (MAC) layer protocols. In this paper we address MAC layer constraints and propose the enhancement that maximizes system efficiency. Developed model is used for optimal frame size adaption and thus reduces time and resources for tags identification.

Paper is structured as follows: Section 2 describes ALOHA protocols as a MAC layer protocol and related works addressing the optimization problems. In Section 3 we describe the model developed to adjust frame length within Dynamic Framed Slotted ALOHA (DFSA) protocol. Section 4 provides the algorithm for adapting frame size as well as results obtained from the simulation. It includes comparison with Q-Selection algorithm, as UHF-RFID standard in [6]. In section 5 we give some concluding remarks and implications for future work.

2 RELATED WORKS AND DYNAMIC FRAMED SLOTTED ALOHA (DFSA) ANALYSIS

ALOHA protocol was at first developed to link campuses on Hawaiian University, but due to its simplyness, and with some modifications ALOHA is used for passive RFID system MAC Mechanisms. Passive RFID systems use DFSA (Dynamic Framed Slotted ALOHA) medium access mechanism, as a upgraded version of pure ALOHA [7].

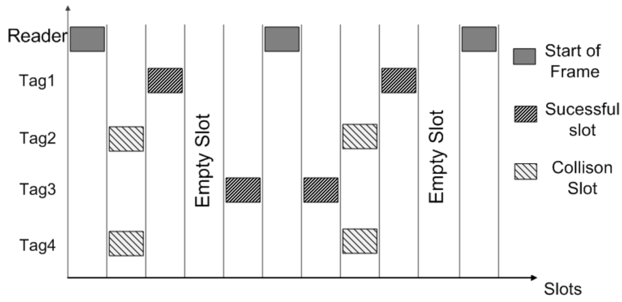

Fig. 1. Example of Framed Slotted ALOHA protocol with length of frame equal to 4, and 4 tags within interrogation area

Mechanism of pure ALOHA protocol was simple for station to send data, as soon as request is received. It reduces system throughput drastically if more than a few stations transmit at the same time, while medium is occupied. To increase system throughput Slotted ALOHA protocol [8] was developed, where stations can transmit during a time slot. However, throughput was still not good enough, because it is not possible to predict the number of slots required for all stations to transmit their data. There were no mechanisms for collisions control, which increased the number of collisions. In order to address collision problems and to increase throughput, Framed Slotted ALOHA was developed [1]. Transmission is then divided into frames, and frames into slots. To make it more efficient, frame length should be adaptive (DFSA) as proposed in [9].

In DFSA protocol reader informs tags about number of slots (frame length) they can take. Reader broadcasts value 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 $QueryREP$, their slot value is decremented by 1. First tag that reaches the zero value sends its information back to the reader. During Reader-Tag communication there are three possible scenarios:

1. There is only one tag in a current slot that the reader is inventorying, which is the successful slot.

2. There is more than one tag in current slot, which is the collision slot, because reader cannot resolve more than one tag signal. If collision tags signal is strong enough, the standard [6] proposes methods for resolving one of them.

3. There is no tag in a current slot, which is the empty slot in a frame.

Figure 1 illustrates Frame Slotted ALOHA where size of frame is 4. With the DFSA protocol, calculation of total

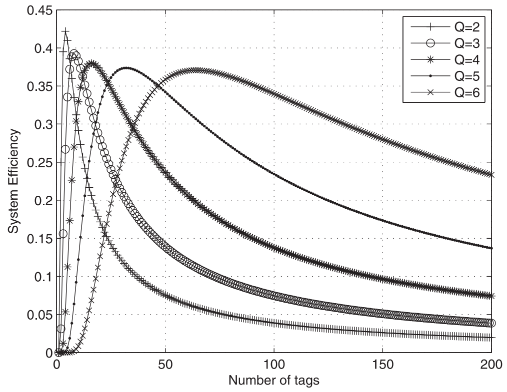

Fig. 2. FSA efficiency for different frame lengths

system throughput is given with [9] :

$$E(p) = Np(1-p)^{(N-1)} \tag{1}$$

where p is probability of of finding each tag within the frame of length L, and N represents total number of tags. In order to find value which provides maximum of function, we derive (1) which results in:

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

Point of maximum value is for $p' = 1/N$, i.e. when frame length equals number of tags, which equals in the maximum throughput $(1/e) = 0.368$. Simulation of the FSA protocol with fixed frame length is depicted in figure 2. The other approach of MAC frame length adaption are binary tree protocols [10] [11], which according to [9] have greater complexity since each garbled (collision) 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 very first papers written about optimization in DFSA [9] describe the problem of number of tags which need retransmission as a $2.39C$ if the number of tags within collision slots (C) is described with Poisson distribution with integer mean value. Schoute analysis gives 42.6% efficiency, instead of upper bound of 36.8%. The observation is a special case when number of retransmissions is exactly specified Poisson distribution.

Vogt's proposal [12] includes Markov process chain and estimation of tags which needs retransmission. Vogt estimates number of tags as a minimum error between number of empty, successful and collision slots and their expected value pairs. It was implemented in Phillips I-code RFID system [13]. To reduce system complexity, available frame lengths were limited to powers of 2, which according to [14] [15] lowers the system throughput to 35%. To obtain maximum throughput, frame size should equal the number of tags in interrogation area. Limitation of frame lengths to the powers of 2 sizes is also specified by EPCglobal in [6]. EPCglobal today leads the development of industry standards for Electronic Product Code in RFID systems.

Improvement of Schoute analysis [16] continues using the expected value of $2.39C$, but in order to combat random jitter during ID collection, a threshold of 1.15 is defined, so retransmission is necessary only if estimated number of tags is greater than 1.15 times than the number of tags in previous frame. Similar work was proposed by [17], and it is based on the fact that outcome of a random process is most likely near the expected value (Chebyshev's inequality).

Author in [18], considers distribution of tags in the frame as a multinomial distribution, where probabilities are calculated from binomial distribution of slot occupancy. The work does not include the fact that the number of tags in interrogation area is a limiting source.

Floekermeier in his papers [14, 19] observes last z frames, and updates the probability distribution whenever tags are departing from interrogation area, so distribution of tags is estimated accordingly.

Liu et al. in [20], consider different slot duration time, which increases the system efficiency. However, the system lacks tags estimation technique, which would also help to increase the efficiency.

EPCglobal proposes the adaptation of the frame size using the Q-Selection algorithm [6], depicted in figure 3. In the Q-Selection reader is sensing environment by broadcasting $Q = 4$. Tags are replying within the frame and the system is counting number of collision and empty slots. If empty slot occurs, Q for the next frame will be:

$$Q_{fp} = max(0, Q_{fp} - C) \tag{3}$$

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

$$Q_{fp} = min(15, Q_{fp} + C) \tag{4}$$

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 $0.1 \leq C \leq 0.5$ is chosen in the way to be small for high tag rate and large for low tag rate. Considering tag price and available functionalities DFSA MAC layer protocol satisfies the requirements. However, there is still a question, how to adapt frame length without any *a priori* knowledge about environment that is interrogated.

Due to tags low computational abilities, there is nothing much we can do, except varying frame size to reduce

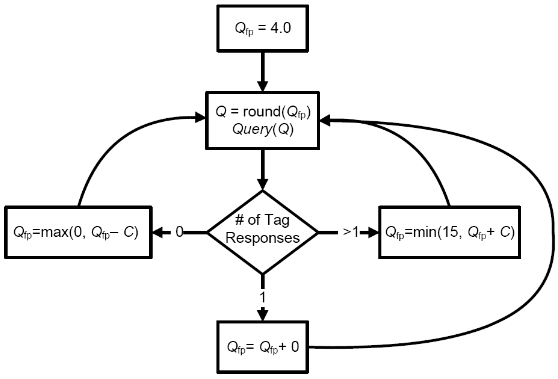

Fig. 3. Q-Selection Algorithm sequence diagram from UHF-GEN2-RFID [6]

the number of collisions and empty slots and increase efficiency of the system. To measure quality of different variants of DFSA, standard measures of System Efficiency and Collision ratio are used.

After tags interrogation, reader will obtain information about successful (S), empty (E) and collision (C) slots. After the reader receives information about slots, in the next section, we propose tag estimation technique which includes combinatorial model of frame and thus, using the results from the model calculate *a posteriori* probability $p(E, S, C \mid n)$. Maximum value from calculated probability distribution is used for the number of tags estimation. Authors previous work analysis on LookUp Algorithm [21] is considered for the system implementation. Work described in [21] proposes usage of model where number of collisions linearly changes as estimated number of tags and number of successful slots changes. Furthermore, to model the system linearity, we use the results obtained from combinatorial model to calculate 4 characteristic points, crucial for the lines modeling.

3 CALCULATING OPTIMAL FRAME SIZE

To determine optimal frame size we need to estimate the number of tags $\hat{n}$ within the interrogation area. We provide $\hat{n}$ by the calculation of the *a posteriori* conditional probability distribution $p(E, S, C \mid n)$, which is described with all possible realizations of given frame (number of E, S, C) with its length L. Maximum of the distribution $p(E, S, C \mid n)$ is used to estimate $\hat{n}$, and thus through

$$\hat{Q} = round(\log_2(\hat{n})) \tag{5}$$

set up the optimal frame size.

A posteriori conditional probability distribution of frame combination E, S, C, for given number of tags n,

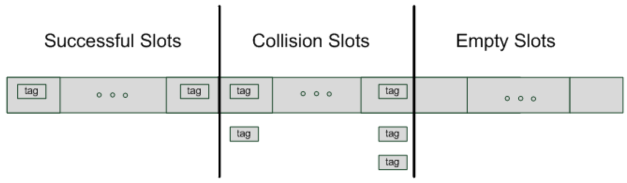

Fig. 4. After reader interrogation, we arrange the frame in the successively array of Successful, Collision and Empty Slots

i.e. $p(E, S, C \mid n)$, is given with:

$$p(E, S, C \mid n) = \frac{\text{all possible outcomes of given } E, S, C}{\text{total number of outcomes for given } n} \tag{6}$$

For counting the number of different slot realizations we consider tag as a unique item, since one tag can be in one slot at the time. Denominator of the fraction (6) is then given with the total number realizations $N(n)$ of given frame for total number of tags n and number of slots L (frame length):

$$N(n) = L^n \tag{7}$$

Equation (7) describes the number of tag variations with repetition in the frame.

To calculate the nominator of (6), we arrange the frame as it is depicted in the figure 4. The arrangement into groups of E, S, C is done to reduce the complexity of observation. Of course, the slots are permutated in-between the frame, which is included by multiplying with multinomial coefficient:

$$\frac{L!}{E!S!C!} \tag{8}$$

Once slots are rearranged, we need to count the number of ways to distribute n tags to S successful slots and C collision slots. The nominator is then given as a product of all possible outcomes of successful $N(S)$, collision $N(C)$ slots and permutations of the E, S, C in-between the frame of length L. Empty Slots did not receive any tags, so we do not have to distribute any tag in those slots. But, empty slots can occur, and they can be anywhere in the slot along with collision and successful slots:

$$nominator = N(S)N(C)\frac{L!}{E!S!C!} \tag{9}$$

Successful slot is the slot where one can find only 1 tag. Since all tags are different, to count the number of ways to distribute n tags to S successful slots, formula for permutations without repetition can be used:

$$N(S) = \frac{n!}{(n-S)!} \tag{10}$$

and it describes on how many ways one can divide tags into slots, so none of the tags enter the same slot.

Collision slot is the slot where we find at least 2 tags. We need to calculate the number of all possible realizations of remaining $n - S$ tags in C collision slots. To count them generating function can be used. Generating functions are algebraic objects whose formal manipulation allows us to count the number of possibilities for a problem by means of algebra. Moreover, generating functions are Taylor series of infinitely differentiable functions. If we find the function and its Taylor series, then the coefficient in expansion of Taylor series give the solution to the problem [22].

Each slot can be described with exponential generating function represented with its Maclaurin series:

$$e^x = \frac{x^0}{0!} + \frac{x^1}{1!} + \frac{x^2}{2!} + \frac{x^3}{3!} + ... = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + ... \quad (11)$$

where coefficient of $x^k/k!$ is the number of variations with repetition of k tags in one slot. To describe collision slot, some restriction have to be imposed. In (11) it means removing the terms $x^0/0!$ and $x^1/1!$ describing empty slots and one tag slot, respectively. After imposing the restrictions, new exponential generating function for collision slot is:

$$e^x - (1 + x) = \frac{x^2}{2!} + \frac{x^3}{3!} + ... \quad (12)$$

Since we have C collision slots, multiplication of series (12) C times provides new series:

$$(e^x - (1 + x))^C = \left(\frac{x^2}{2!} + \frac{x^3}{3!} + ...\right)^C \quad (13)$$

For the expansion (13), $N(C)$ is the coefficient of $x^{(n-S)}/[(n - S)!]$, which counts the number of possible ways to distribute remaining $n - S$ tags to collision slots. One way to obtain the value of $N(C)$ from (13) is to pick out the terms in x^{n-S}, and multiply it through by $(n-S)!$.

Finally, total distribution $p(E, S, C \mid n)$ is provided using the (7), (8),(10),(13):

$$\begin{aligned} p(E, S, C \mid n) &= \frac{N(S)N(C)\frac{L!}{E!S!C!}}{L^n} \\ &= \frac{\frac{n!}{(n-S)!}\left(e^x - (1 + x)\right)^C \mid_{\frac{x^{(n-S)}}{(n-S)!}} \frac{L!}{E!S!C!}}{L^n} \end{aligned} \quad (14)$$

Simulation of the model described with (14), as well as simulation of FSA for the frame with the length $L = 16$ is depicted on the figure 5. Using the:

$$\underset{n}{\text{argmax}} \{p(E, S, C \mid n)\} \quad (15)$$

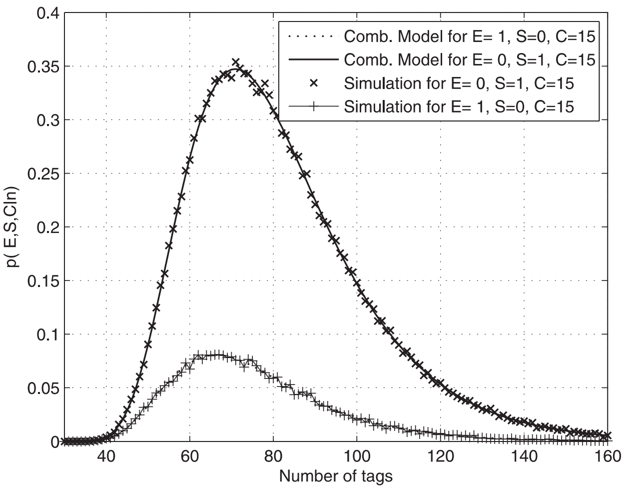

Fig. 5. Results of FSA simulation and Combinatorial model in (14). The maximum of depicted distributions $p(E, S, C \mid n)$ is used as estimation of number of tags within interrogation area.

we obtain estimated number of tags $\hat{n}$, and thus, through the (5), set the optimal frame size.

In the model implementation, the part (13), might not be in appropriate form for adoption in real RFID systems, because of its calculation complexity. We suggest, for the algorithm implementation to combine the linear model behavior for optimal frame size selection described in [21] with the combinatorial model provided in this paper. In [21], authors provide experimentally obtained linear model, as depicted in figure 6. Lines in figure 6 which are equidistant, within the graph whose parameter is the number of collisions, change linearly when successful slots and estimated number of tags change. The algorithm includes pre-calculating 4 characteristic points per frame size, that form 1^{st} and penultimate line. Lines in between, $2^Q - 3$ of them, are equidistant.

First point is for 0 collisions and 0 successful slots, that trivially equals 0 with probability 1. Second point that will construct first line is for 0 collisions and L (all) successful slots, that also trivially result with L tags. Third point is for $allcollision - 1$ and 0 successful slots, and is provided with:

$$\underset{n}{\text{argmax}} \{p(1, 0, L - 1 \mid n)\} \quad (16)$$

with the fourth point $allcollision - 1$ and 1 successful slot, creates penultimate line, defined as:

$$\underset{n}{\text{argmax}} \{p(0, 1, L - 1 \mid n)\} \quad (17)$$

In this algorithm we did not provide all-collision scenario (last line) because it results with maximum in infinity of

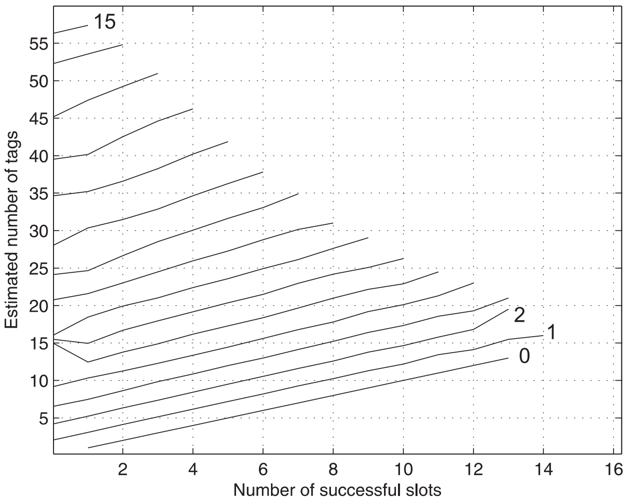

Fig. 6. Linear model behavior of the frame ($L = 16$) obtained experimentally in [21]. Lines represent collisions, $0 - 15$, down-up. 16^{th} line is a point, because all-collision scenario results with 0 successful slots

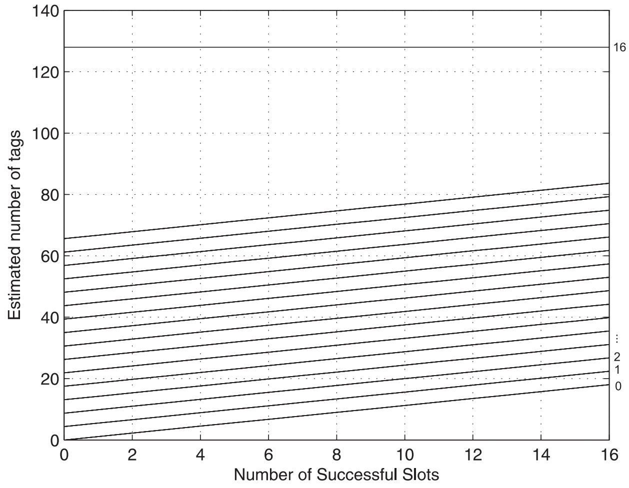

Fig. 7. Linear model behavior of the frame ($L = 16$) obtained from combinatorial model. Lines represent collisions, $0 - 15$, down-up. Last line, for all collision scenario is in this case $n = 2^{Q_{current\,frame}+3} = 2^7 = 128$

$p(E, S, C \mid n)$. But in [21], simulation shows that all collision scenario will result with the next frame size greater by factor $Q = 3$ than one in the last frame. After the implementation of the lines, we obtain example scenario for $Q = 4$, depicted in figure 7.

4 THE ALGORITHM AND RESULTS ANALYSIS

The algorithm for optimal frame size selection is given with Algorithm 1. As in Q-Selection, for the environment sensing,start value of $Q = 4$ is used, as a value which is not big nor small. Impact of choosing initial frame size is studied by [9] [12] [18]. After the algorithm simulation we calculate System Efficiency as:

Algorithm 1 Algorithm for Selection of the Optimal Frame Size

Input: E, S, C, L

Output: adapted $\hat{Q}$

1. sense the environment by broadcasting single $Q = 4$
2. calculate 4 characteristic points from L using $p(E, S, C \mid n)$
3. create the equidistant lines
4. last line, line for $C = 2^Q$, sets $\hat{n} = 2^{(Q_{\text{last frame}}+3)}$
5. find estimated number of tags $\hat{n}$ (point on the line), using (S, C), and set $\hat{n} = \hat{n} - S$, because S tags have already been read in the current frame.
6. calculate $\hat{Q} = round(\log_2(\hat{n}))$
7. Broadcast new $\hat{Q}$

$$\text{System Efficiency} = \frac{S}{E + S + C} \tag{18}$$

Another measure of the system quality, is the Collision Ratio, defined as:

$$\text{Collision Ratio} = \frac{C}{E + S + C} \tag{19}$$

To measure the algorithm quality, we compare simulation results with Q-Selection Algorithm. System efficiency and collision ratio are depicted in figure 8 and figure 10. System Efficiency of the Combinatorial model shows better performance than Q-Selection for each tag number.

Results for Q-Selection is for constant value $C = 0.1$, as best chosen C for high tag rate [17]. Low collision ratio of Q-Selection algorithm results with higher empty slots ratio, because of lower efficiency than Combinatorial model. It means that Q-Selection algorithm for higher tag ratio estimates larger frame size, and thus increases the number of empty slots. Authors in [17] provide mean collision ratio value of 0.25 for their algorithm approach; however our work lowers it on several segments as it is depicted in figure 10.

Moreover, to measure the quality of $\hat{Q}$, we provide the analysis on the error $Q_e = \hat{Q} - Q$, where $Q = round(log_2(n))$. It is obtained using Monte Carlo simulation of random tag number generation, in the range from 1-500 tags, where collision ratio and system efficiency are calculated. After the simulation, the error Q_e is calculated. To ensure the convergence of the error, experiment of random tag number generation is repeated 10 000 times, for the each $Q's$ optimal range. Optimal range for the each Q includes the set of n, where infimum and supremum are the lowest and highest value of n, satisfying

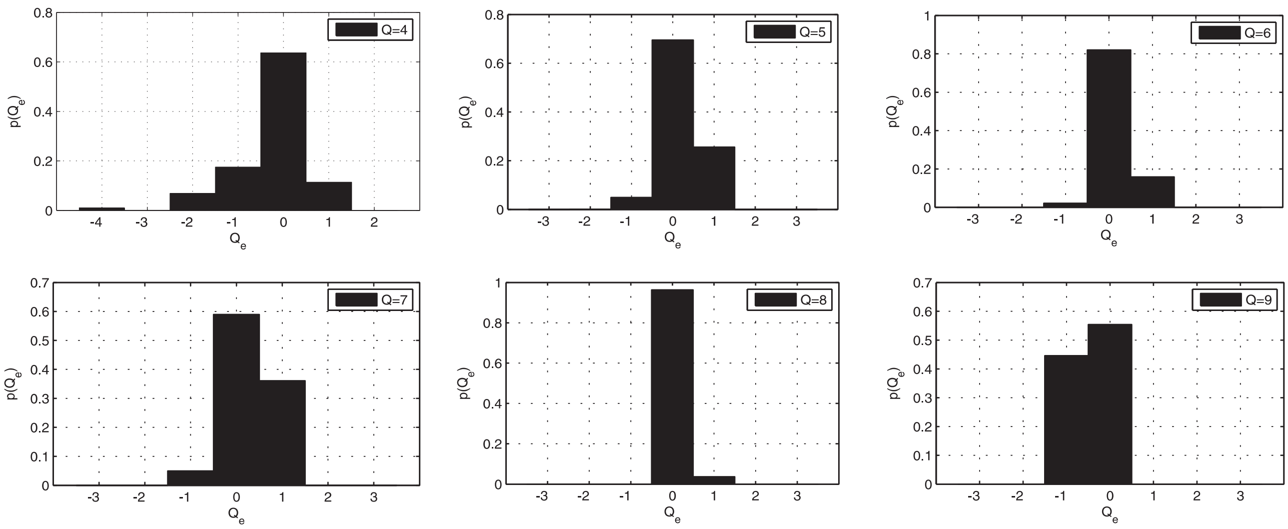

Fig. 9. Histogram of error for different values of Q

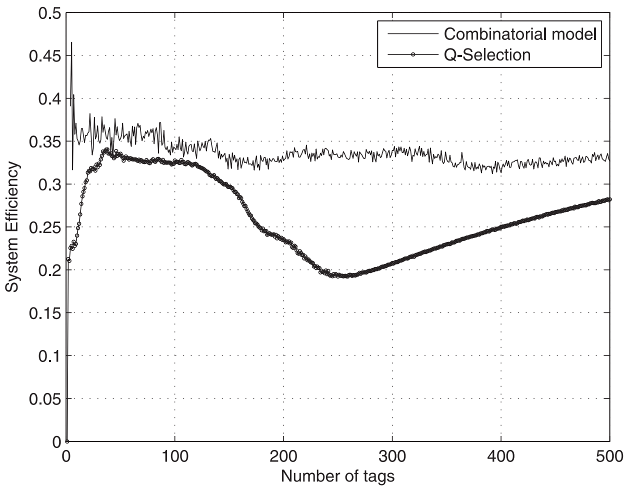

Fig. 8. Using the combinatorial model, and lines setup, we calculate System Efficiency defined as (18)

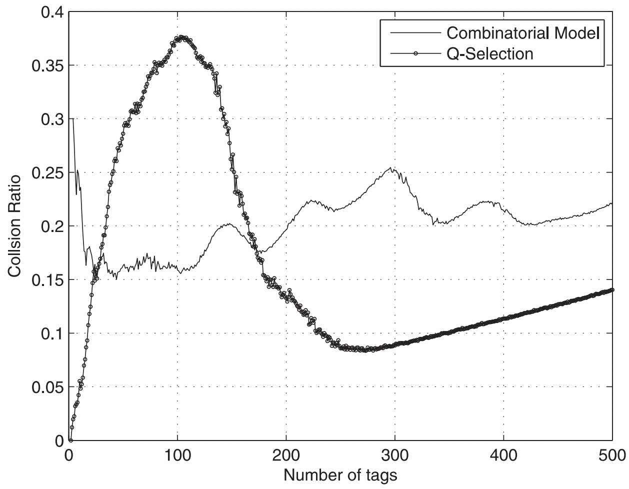

Fig. 10. Using the combinatorial model, and lines setup, we calculate Collision Ratio defined in (19)

$Q = round(log_2(n))$ for the exact Q. Results are depicted in figure 9. The error for $Q = 9$ is higher because of top bound of 500 tags. $Q = 9$ is optimal for the number of tags up to 724.

5 CONCLUSION

In this paper we proposed the algorithm for optimal frame size selection. To set optimal frame size, one needs to estimate number of tags in the interrogation area. Estimated number of tags is calculated through the maximum of the conditional probability $p(E, S, C \mid n)$, where we showed that our model equals the simulation of FSA protocol. However, the calculation of the conditional probability is not simple, so we proposed calculation of 4 characteristic points defining the linear model describing estimated number of tags for all possible realizations (E, S, C) of given frame size. Those points are used for equidistant lines construction, and thus to derive optimal frame size by finding the value on the line.

Algorithm steps are easy for system implementation, using simple operations of multiplying and additions, similar as in Q-Selection. Implementation of the proposed model includes equidistant lines construction, and finding the estimate is simply finding the point on the line $y = ax + b$, where a is constant, and b changes linearly. Simulation of Combinatorial model with the lines implementation shows that System Efficiency of Combinatorial model algorithm shows better performances than Q-Selection Algorithm.

Future work will include algorithm implementation using A Flexible Software Radio RFID Reader, which is built using USRP Software Radio Platform in conjunction with GNU radio framework, developed by [23]. Algorithm implementation will make possible a working comparison with Q-Selection as well as the implementation of the other author algorithms.

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