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Nilsson B, Bengtsson L, Svensson B. Selecting back off algorithm in active RFID CSMA/CA based medium-access protocols. In: International Symposium on Industrial Embedded Systems, 2008. SIES 2008. New York: IEEE; 2008. p. 265-270.

DOI: http://dx.doi.org/10.1109/SIES.2008.4577714
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Selecting Back-Off Algorithm in Active RFID CSMA/CA Based Medium-Access Protocols

Björn Nilsson, Lars Bengtsson, *Senior Member, IEEE*, and Bertil Svensson, *Member, IEEE*

***Abstract*—Active Radio Frequency Identification (A-RFID) is a technology where the tags (transponders) carry an on-board energy source for powering the radio, processor circuits, and sensors. Besides offering longer working distance between RFID-reader and tag than passive RFID, this also enables the tags to do sensor measurements, calculations and storage even when no RFID-reader is in the vicinity of the tags. In this paper we study the effect on tag energy cost and read out delay incurred by some typical back-off algorithms (constant, linear, and exponential) used in a contention based CSMA/CA (Carrier Sense Multiple Access/ Collision Avoidance) protocol for A-RFID communication.**

For the type of A-RFID scenarios considered, where the number of tags is varied as well as how fast they pass a reader, simulation results show the importance of selecting the correct length of the Initial Contention Window (*ICW*) and the algorithm coefficient based on the number of tags.

The study also indicates that by dynamically selecting the proper back-off algorithm coefficients (based on the number of tags), viz. the initial contention window size and the back-off interval coefficient, the tag energy consumption and read-out delays can be significantly lowered compared to using a static back-off algorithm.

I. INTRODUCTION

A. *Passive and Active RFID*

The most common Radio Frequency Identification (RFID) technology today is passive RFID ("P-RFID"). The tags have no energy source but instead they are powered by the reader transmitting a magnetic field or RF energy which is converted to electrical power by the tags. Although this enables low-cost tags the main drawbacks are: 1) the limited working distance between reader and tag (in the order of a few meters); 2) the high transmitted reader energy required; and 3) sensor readings and calculations are not possible when no reader is in the vicinity to power the tags.

In active RFID ("A-RFID") the working distance can be much longer (in the order of a few hundred meters). A-RFID tags, having their own power source, can use higher transmit power and receivers with higher sensitivity. Another benefit is that sensor measurements, calculations, and storage are possible even when no reader is in the vicinity of the tags.

The reader in P-RFID systems has to continuously radiate high energy to power the tags while that is not the case in active systems. Also, in the case where a large area has to be covered, many readers have to be used in passive systems while only a few in active ones. The possible rate of detecting tags is dependent on a combination of range and output power from the reader. For scenarios which need fast detection of tags this implies dense readings close to the reader in P-RFID. A-RFID systems can spread the readings in the time domain and in distance from the reader and therefore offer a higher throughput of tag readings.

B. *Application Scenarios*

A typical application where A-RFID is used is in the logistics chain management, where there is a need to track a product from the manufacturer to the consumer [1]. A scenario in such an application is the fork lifter carrying a pallet loaded with items each with an A-RFID tag. There could be hundreds of tags that must be read in short time (a burst of finite traffic) while the fork lifter passes the reader. Moreover, this should be done using minimal energy in order to save tag battery life time.

Another scenario is the constant reading of tags in a warehouse where thousands of items are stored and need to be kept track of in real time. This requires many readers or readers with the ability for far distance readings such as the one that an A-RFID system permits. Also here there is an interest in minimizing the tag energy needed. However, the requirement for a fast reading rate is not as strong as in the first scenario.

C. *Purpose of This Work*

Earlier studies conducted at CERES (Center for Research on Embedded Systems) show that carrier sense is of great importance for lowering the energy consumption in A-RFID [2, 3]. The carrier sense functionality that is used to avoid collisions in protocols also needs some type of back-off algorithm to be effective. This paper is focused on the back-off algorithms.

The purpose of this work is to investigate, by simulations, the energy consumption and read out delays incurred by five different back-off algorithms (constant, linear, linear modulus, exponential, and exponential modulus), and their back-off coefficients and Initial Contention Windows.

This work was supported in part by Center for Research on Embedded Systems (CERES), Free2move AB, and the Knowledge Foundation.

B. Nilsson is with the CERES at Halmstad University, Halmstad, SWEDEN, and the company Free2move AB, Halmstad, SWEDEN. (E-mail: bjorn.nilsson@ide.hh.se)

L. Bengtsson is with CERES, and the Department of Computer Science and Engineering, Chalmers University of Technology, Göteborg, SWEDEN.

B. Svensson is with CERES at Halmstad University, Halmstad, SWEDEN.

978-1-4244-1995-1/08/$25.00 ©2008 IEEE.

II. RELATED WORK

Published work on back-off algorithms in A-RFID seems to be scarce. However, research work has been done to achieve higher efficiency (fewer collisions on the radio channel) in the IEEE 802.11 standard by apply a back-off strategy. For instance, Taifour et al. [4] propose a neighborhood back-off algorithm (NBA) where the initial back-off interval relies on the number of neighbor nodes. The required minimum contention window is shown to be proportional to the number of neighbors. Experiments also show that the NBA shows better behavior than the often used Binary Exponential Back-off (which is a special case of exponential back-off with the back-off factor set to 2).

Jayaparavathy et al. [5] suggest that the back-off time for each contending node can be modified by retrieving information (delay from the contending nodes) obtained by transmitting stations and thereby getting higher throughput and shorter delays.

Bhandari et al. [6] present simulation results that show that, by using binary slotted exponential back-off, the throughput and delay is sensitive to the initial back-off window size, the payload size and the number of stations in the network. The results can be used to decide the protocol parameters for optimum performance under different loading conditions.

An algorithm in which exponentially increasing/ decreasing (EIED) back-off is used is presented by Song et al. [7]. They also provide an analysis of EIED back-off algorithms and an optimizing methodology.

An alternative back-off policy that is called the µ-law or the step function can outperform the exponential back-off, as shown by Joseph et al. [8]. These back-off algorithms consider slower reduction of the back-off time in the initial phase of back-off and then a more rapid reduction.

A distributed back-off strategy to achieve lower power consumption has been studied by Papadimitratos et al. [9], delivering 154% more data bits per unit energy consumed in the network. This is done by determining the back-off period for each transmitting node based on the node's wireless link quality. The better the link quality is the shorter back-off period is used.

It is possible to modify and use some of the related work. For instance the reader could gather some statistics about the number of tags usually in reach of it. By using this statistics, back-off time as well as parameters of importance to the tag, can by dynamically adapted.

A. *The A-RFID MAC Protocol*

The Medium Access protocol that we model in our study is a contention based CSMA/CA (Carrier Sense Multiple Access/ Collision Avoidance) protocol [10]. When a tag wants to transmit a payload packet it starts by doing a carrier sense to see if anyone else is currently transmitting, see Figure 1. If so, the tag waits a specific time ("back-off") until it retries. When the packet subsequently is successfully delivered to the reader, the reader transmits an acknowledge packet to the tag which then enters sleep mode. Our interest is to determine how this back-off should be selected in order to minimize the energy consumption and the read-out delay.

In our fork lifter scenario (carrying a pallet with hundreds of A-RFID tags) the reader initially awakes the tags when the fork lifter is approaching and in range using a beacon message. This message contains two parameters: 1) *ICW*: the time period (initial contention window) during which all tags must do their first transmission attempt; 2) a coefficient (explained below).

The tag uses the information to select a stochastic (evenly distributed) initial back-off time (t_0) during the *ICW* and calculates the subsequent back-off times using the appropriate algorithm and coefficient, shown in Figure 2.

After the initial back-off time the tag performs a carrier sense to detect if any other tag is using the radio channel. If the channel is free the tag transmits its payload packet and waits for an acknowledgement from the reader. If the channel is occupied the tag performs a new back-off.

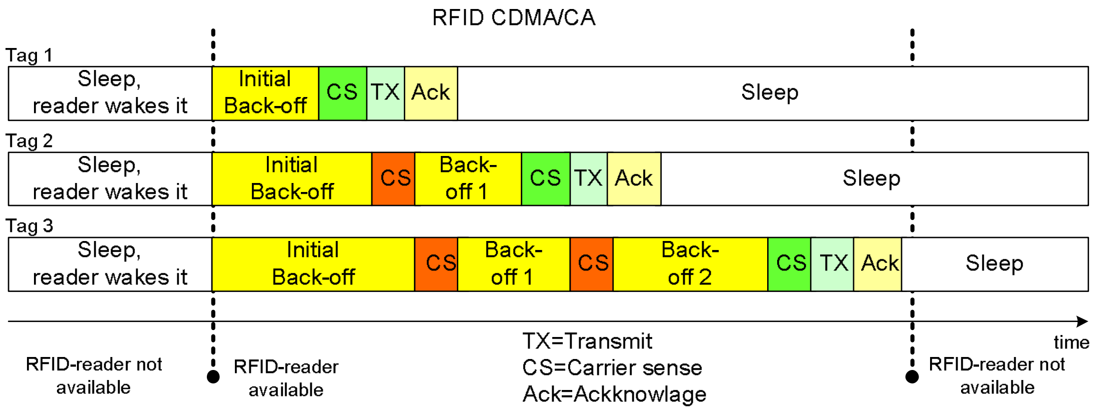

Figure 1: Tags delivering their payload packets to a reader.

III. BACK-OFF ALGORITHMS

The five types of back-off algorithms studied are: *constant* (1), *linear* (2), *linear modulus* (3), *exponential* (4), and *exponential modulus* (5). The equations below describe the five algorithms. Their behaviors are also depicted in Figure 2.

Constant back-off:

$$t_{i+1} = t_i + C \cdot T_{slot} \tag{1}$$

Linearly increasing back-off:

$$t_{i+1} = t_i + L \cdot i \cdot T_{slot} \tag{2}$$

Linearly increasing back-off with modulus:

$$t_{i+1} = t_i + L \cdot (i \bmod r + 1) \cdot T_{slot} \tag{3}$$

Exponentially increasing back-off:

$$t_{i+1} = t_i + E \cdot 2^{i} \cdot T_{slot} \tag{4}$$

Exponentially increasing back-off with modulus:

$$t_{i+1} = t_i + E \cdot 2^{(i \bmod r)} \cdot T_{slot} \tag{5}$$

Here, C, L, and E are coefficients, $i = 0, 1, 2..$ is the back-off sequence number, and t_i is the absolute time at sequence number i. The modulus operator "mod" in equations (3) and (5) restarts the back-off counter after r back-offs. In our simulations we used $r = 5$. T_{slot} refers to the time to do one TX and one RX, in total 3.6ms (1.6ms+2.0ms).

IV. SIMULATION SETUP

Here we present the physical constraints of the radio channel, the simulation method and the simulation model.

A. Radio Channel Model

The radio channel model used in our simulations is an error-free radio channel and a non-persisting carrier sense multiple access protocol with collision avoidance (CSMA/CA) using a non-slotted channel. The radio signal propagation delay is neglected because of the short working distances.

The A-RFID system modeled is built using the physical constraints of a commercially available transceiver working in the 2.45 GHz ISM band with a bit rate of 250 kbit/s [11]. It has a working range of 50 m in free space. The output power has a maximum of 0 dBm (1 mW), a receiver sensitivity of –90 dBm, and a channel bandwidth of 1 MHz.

B. Simulation Method and Model

All simulations are done using Matlab and begin with a user population of 50 tags available to the reader. Simulations are then done for an increasing number of tags until reaching 1050. All tags wake up simultaneously when there is a reader in the vicinity, without consuming any energy and in zero time. Every tag has to deliver its payload packet and receive an acknowledge packet before the simulations ends. Both the payload and the acknowledge packets are 200 bits long. The propagation time for packets to and from the reader is assumed to be zero due to short distances.

The *constant*, *linear*, and *exponential* back-off algorithms are simulated with their coefficients, C, L, and E respectively, stepped in the range from 1 to 100. The variable *ICW* is in the range from 100 ms to 4900 ms in steps of 300 ms. Figure 3 depicts the simulation procedure. The results from the simulations are the delay and the number of performed carrier senses, one for every back-off. This is repeated 100 times, after which an average value is calculated.

Each tag makes a first initial random back-off in the *ICW*. On waking, the simulated tag does a carrier sense, and if the radio channel is free (no other tag, nor the reader, is doing a transmission) a payload packet is transmitted to the reader. If the radio channel is occupied the tag makes a new back-off. A small random time is also added to prevent tags from trying to communicate periodically at the same time (shown as shadowed in Figure 2). This randomness is a time between 0 and 7.2 ms (which is the time to do two RX and two TX using the modeled transceiver).

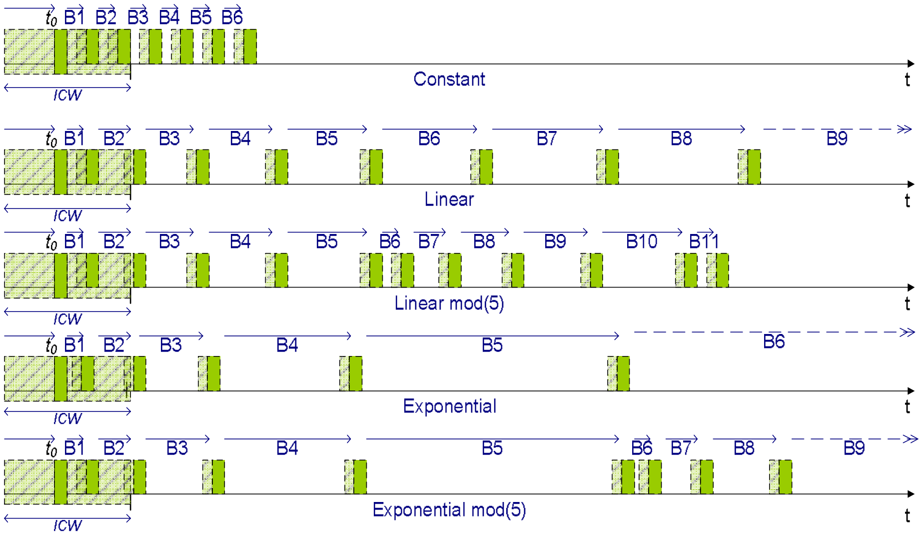

Figure 2: Types of back-off algorithms: constant, linear, linear modulus, exponential, and exponential modulus. The arrow ending at time t_o (randomly chosen by each tag in the range of the *ICW*) is the initial back-off, then increasing B-numbers show successive back-offs. Shadowed parts show randomness in the back-off time which is added to each t_i.

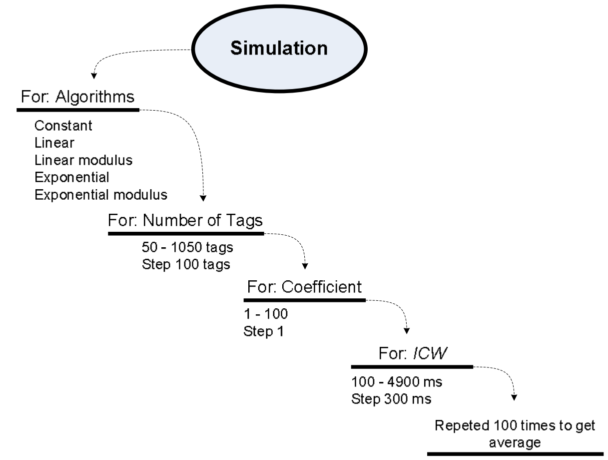

Figure 3: The simulation procedure.

V. RESULTS

Applications using A-RFID need to be optimized both for long lifetime and for short delays. Unfortunately, these two goals are in conflict with each other, so a trade off is necessary. In this section the performance of each of the algorithms is analyzed by extracting data from simulations and calculating the tag energy consumption and the tag read out delay. The algorithms are then compared over a large application space (finding, for different numbers of tags, the minimum energy consumption and minimum read out delay possible by choosing the best coefficient and the best *ICW*).

A. Energy, Delay and EDP

The simulation results are presented in the form of: 1) Energy, which is the energy consumption per delivered payload packet; 2) Delay, which is the read out delay; and 3) Energy Delay Product (*EDP*), for overall comparison of algorithms.

In Figures 4 through 8, one for each of the algorithms, *Energy*, *Delay* and *EDP* are shown as a function of the number of tags and the coefficient. Both energy and delay also depend on the *ICW*, but this is not shown in the figures. Instead, the minimum values, when the *ICW* is varied, are presented, see equations (6), (7), and (8). The $Energy_S$ in average consumed by a tag is for doing all necessary carrier senses, transmitting one payload packet and receiving one acknowledge packet. The read out delay, $Delay_S$, is the average time until every available tag has delivered one payload packet.

$$Energy\left(\#tags, coeff\right) = \min_{ICW} Energy_S\left(\#tags, coeff, ICW\right) \tag{6}$$

$$Delay\left(\#tags, coeff\right) = \min_{ICW} Delay_S\left(\#tags, coeff, ICW\right) \tag{7}$$

$$EDP_S\left(\#tags, coeff, ICW\right) = Delay_S \cdot Energy_S \tag{8}$$

Figure 4 shows results from simulation of the constant back-off time algorithm. The energy diagram of Figure 4 shows the energy consumption in Joule for a tag in delivering a payload to the reader. A maximum in energy consumption can be seen when there are 1050 tags and a small coefficient *C*. The middle diagram in Figure 4 shows the *Delay* in seconds. The longest delay exists when there are 1050 tags and a large *C*, and then successively a somewhat shorter delay when decreasing *C*.

In an attempt to compare the algorithms over the entire application space (different number of tags and acceptable delays) the *EDP* metric has been used. The *EDP*, see equation (9), is the minimum of the product of energy and delay for each number of tags and each coefficient when varying the *ICW*, shown in the bottom of Figures 4 through 8. For each number of tags there also exists a minimum *EDP* (se equation 10) and these values are presented as dots connected with a white line in the *EDP* graph. For instance, when there are 550 tags in the vicinity of the reader, *EDP* has a minimum when *C*=15.

$$EDP\left(\#tags, coeff\right) = \min_{ICW} EDP_S\left(\#tags, coeff, ICW\right) \tag{9}$$

$$EDP_{\min}\left(\#tags\right) = \min_{coeff} EDP\left(\#tags, coeff\right) \tag{10}$$

The *ICW* values are extracted from the simulations separately and are not shown in the diagrams

When comparing the diagrams, take notice of the different scales on the y-axis for the different algorithms.

As said, there is a tradeoff between energy consumption and delay. Decreasing one will increase the other.

Conclusions from the figures are that one can minimize with regard to energy consumption or delay or choose a compromise of both. By analyzing the simulation data for different numbers of tags, decisions can be made on how to choose algorithm, coefficient, and *ICW* for a certain application. To achieve an energy efficient protocol one should dynamically select the back-off algorithm, the coefficient, and the *ICW*, depending on the application.

B. Average EDP

An A-RFID protocol should support different types of workloads, characterized by the number of tags passing the reader and how fast they pass (thus stating the acceptable delay). To compare how the algorithms behave under different loads an average *EDP* value has been calculated (11). *n* is the incremental factor used to calculate the number of tags, and min(*EDP*) is lowest *EDP* possible with that number of tags.

$$Avr\,EDP = \frac{\sum_{n=0}^{10} EDP_{\min}(n \cdot 100 + 50)}{11} \tag{11}$$

The average *EDP* is shown in Table 1. By using modulus 5 on the back-off counter, the average *EDP* can be lowered. In the case of the linear algorithm the improvement is 10%. Notable is how the exponential algorithm without modulus really shows poor performance. The improvement with the modulus operation is significant, 88%.

Table 1: Average *EDP*.

Algorithm	**Average *EDP* [mJoule Second]**
Constant	0.61
Linear	0.67
Linear modulus	0.60
Exponential	5.00
Exponential modulus	0.60

VI. CONCLUSIONS

For the type of A-RFID scenarios considered, where the number of tags is varied as well as how fast they pass a reader, simulation results show the importance of selecting the correct length of the Initial Contention Window (*ICW*) and the algorithm coefficient based on the number of tags.

In some scenarios the delay is of prime concern, and in some the number of tags. In all cases the energy consumption is important. Considerable energy consumption savings and read-out delay decrease can be achieved by using modulus on the back-off counter, especially in the exponential algorithm case. Also, the exponential algorithm has long delays when the amount of tags is large, and it should therefore not be used for these applications (Figure 7).

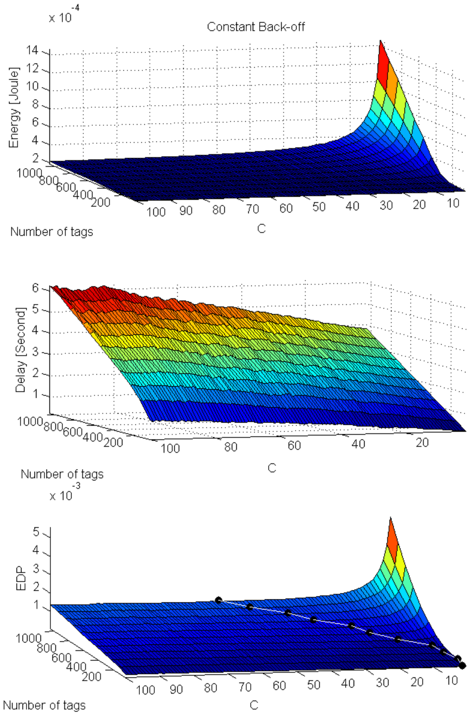

Figure 4: Constant back-off time min Energy Consumption (top), min Delay (middle), and Energy-Delay Product (bottom) as a function of the coefficient C, and the number of tags.

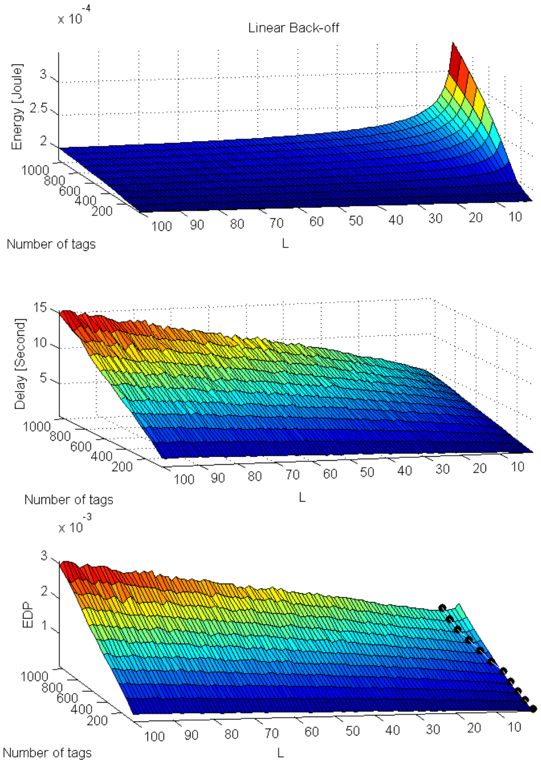

Figure 5: Linear back-off algorithm.

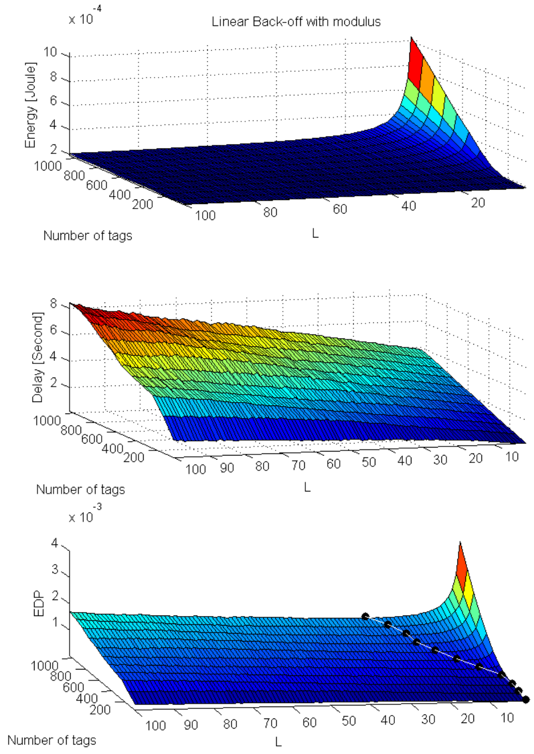

Figure 6: Linear back-off algorithm with modulus.

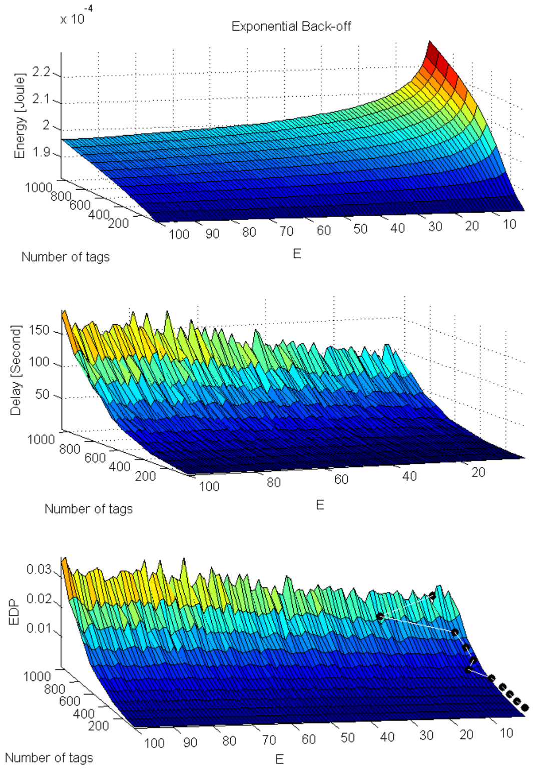

Figure 7: Exponential back-off algorithm.

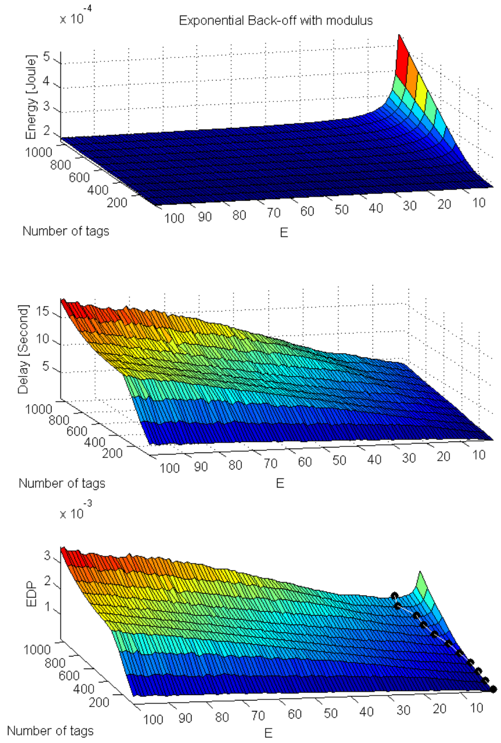

Figure 8: Exponential back-off algorithm with modulus.

REFERENCES

[1] R. Weinstein, “RFID: A Technical Overview and its Application to the Enterprise”, *IT Professional*, Volume 7, Issue 3, May-June 2005, Pages:27-33

[2] B. Nilsson, L. Bengtsson, P-A. Wiberg, and B. Svensson, “Protocols for Active RFID — The Energy Consumption Aspect”, *IEEE Second Symposium on Industrial Embedded System*, Lisbon, Portugal, 4-7 July 2007, Pages 41-48

[3] B. Nilsson, L. Bengtsson, P-A. Wiberg, and B. Svensson, “The Effect of Introducing Carrier Sense in an Active RFID protocol”, Technical Report IDE0766, February 2007

[4] M. Taifour, F. Nait-Abdesselam, and D. Simplot-Ryl, “Neighborhood Backoff Algorithm for Optimizing Bandwidth in Single Hop Wireless Ad-Hoc Networks”, *2005 International Conference on Wireless Networks, Communications and Mobile Computing*, 13-16 June 2005, Volume 1, Page: 336 - 341

[5] R. Jayaparvathy, S. Rajesh, S Anand, and S. Srikanth, “Delay Performance Analysis of 802.11”, APCC 2003, *The 9th Asia-Pacific Conference on Communications*, 21-24 September 2003, Volume 1, Pages: 223-226

[6] B.N. Bhandari, R.V.R. Kumar, R. Banjari, and S.L. Maskara, “Sensitivity of the IEEE 802.11b MAC Protocol Performance to the Various Protocol Parameters”, *ICCCAS 2004, International Conference on Communications, Circuits and Systems*, 27-29 June 2004, Volume 1, Pages: 359-363

[7] N. Song, B. Kwak, and L.E Miller, “Analysis of EIED Backoff Algorithm for the IEEE 802.11 DCF”, *VTC-2005-Fall, 2005 IEEE 62nd Vehicular Technology Conference*, 25-28 September 2005, Volume 4, Pages:2182-2186

[8] K. Joseph, D, Raychaudhuri, ”Analysis of Generalized Retransmission Backoff Policies for Slotted-ALOHA Multiaccess Channels”, *ICC 88, IEEE International Conference on Communications*, 12-15 June 1988, Volume 1, Pages: 430-436

[9] P. Papadimitratos, A. Mishra, and D. Rosenburgh, “A Cross-Layer Design Approach to Enhance 802.15.4”, *MILCOM 2005. IEEE Military Communications Conference*, 17-20 October 2005, Volume 3, Pages: 1719-1726

[10] R. Rom and M. Sidi, *Multiple Access Protocols Performance and Analysis*. Springer-Verlag 1990, ISBN 0-387-97253-6

[11] nRF2401A, Single *Chip 2.4 GHz Transceiver Product Specifiction*, Nordic Semiconductor ASA, 2007