An Application Dependent Medium Access Protocol for Active RFID Using Dynamic Tuning of the Back-off Algorithm

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***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 introduce a medium access data communication protocol which dynamically adjusts its back-off algorithm to best suit the actual active RFID application at hand. Based on a simulation study of the effect on tag energy cost, readout delay, and message throughput incurred by some typical back-off algorithms in a CSMA/CA (Carrier Sense Multiple Access / Collision Avoidance) A-RFID protocol, we conclude that by dynamic tuning of the initial contention window size and back-off interval coefficient, tag energy consumption and read-out delay can be significantly lowered. We also present specific guidelines on how parameters should be selected under various application constraints (viz. maximum readout delay; and the number of tags passing).

Keywords ; Active RFID, protocol, back-off, algorithm

I. INTRODUCTION

Radio Frequency Identification, RFID, has been around since the middle of the last century and has been growing in usage every year. The RFID technique is used to remotely and wirelessly identify a device named *transponder* (or ***tag***) by using an *interrogator* (or ***reader***). The tag has a unique identity used to identify the object it is attached to. The RFID technology can be divided into three main categories, Passive RFID (P-RFID), Active RFID (A-RFID), and semi-passive/active (S-RFID). This work investigates the possibilities of defining an A-RFID protocol that grasps over a set of applications without deteriorating the performance regarding tag life-time and read-out delays. For this to be possible, the protocol must be adaptable to the specific application at hand.

A. *Application Scenarios*

Automation in logistics has driven the development of RFID in the past years. Scenarios for RFID might for instance be in the logistic chain, tracking goods from the producer to the consumer, where the goods can be a single product or up to several hundred products on a single pallet. Items must be identified fast by the RFID-reader when e.g. a fork lifter transports them (Figure 1, lower) passing an RFID-reader. In this realm, RFID could also be used for automatic inventory of the stock in a warehouse (Figure 1, upper), where the reading delay is not critical but where there is a huge amount of tagged goods to identify.

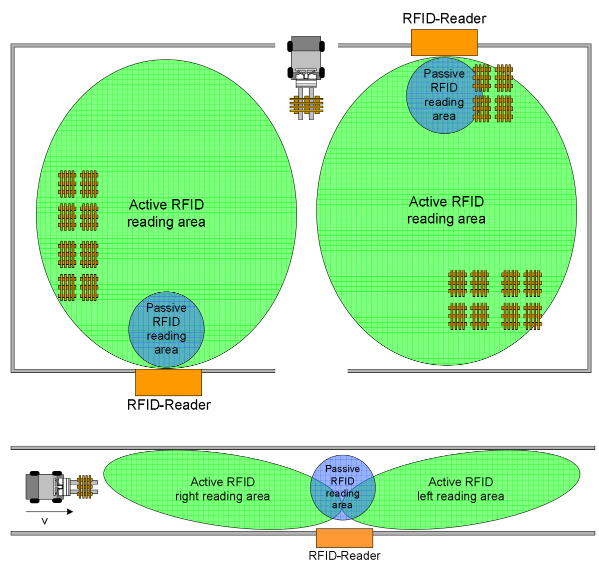

Figure 1. The warehouse scenario where a large amount of goods are stored and have to be continuously updated in the inventory database (upper). The fork lifter scenario where the goods on the pallet have to deliver their identity fast when the fork lifter passes the RFID-reader (lower).

In some applications the physical constraints (e.g. radiated power from the reader) of the RFID-system set the limit of functionality (e.g. limits the reading range). The RFID-reader in the fork lifter scenario needs only a small amount of energy, due to the short distance, but needs fast readings due to the high vehicle velocity. For the warehouse scenario, with long distances, the reader needs to radiate high energy – unless many RFID-readers are used (yielding the well known drawback with the "multi reader problem", where readers

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interfere with each other, which deteriorates readability), however this scenario has no hard read-out time requirements.

B. Today's Standards and Protocols

Standardization of RFID has been going on for some years and has led to different standards used for different applications and in different parts of the world. There are also many proprietary "standards" which do not share the same properties (e.g. information format/storage and physical communication) [1]. To accomplish the usage of RFID-systems worldwide there should be an agreement on a standard (or maybe a few standards).

A lot of standardization work has been done for P-RFID, and the EPC UHF GEN2 defacto standard [2] (work of AUTO-ID Center [3], originally initiated by Massachusetts Institute of Technology) is suggested to be adopted as an ISO standard in the near future. The majority of A-RFID protocols are proprietary. However, some existing standards used in WLAN and Zigbee are currently being used in A-RFID protocols despite their disadvantages regarding tag price and battery life-time [4].

C. Standards for A-RFID

The standard ISO 18000-7 [5] defines the air interface for a device acting as an active tag in the 433 MHz band. Its purpose is to provide a common technical specification for A-RFID devices that is intended to be used by ISO committees developing RFID application standards. An implementation [6] of ISO 18000-7 shows good readability but rather poor performance for dense tag applications, due to the arbitration technique used and the long time to retrieve tag information. Yoon et al. [7] propose a modified tag collection algorithm based on slotted ALOHA that complies with the ISO 18000-7. This modified algorithm allows choosing an optimum slot size for receiving one tag response according to its data processing capabilities.

D. Paper Outline

The outline of this paper is as follows. In Section II, differences in passive and active RFID are discussed, and Section III present related research work. Section IV introduces the suggested, application sensitive, A-RFID protocol which is built on the idea of adaptively choosing the best back-off algorithm parameters. Section V shows the setup for the simulation that we use for simulating the behavior of five different back-off algorithms, and describes the protocol and the five algorithms. Then Section VI shows simulation results. Section VII explores the design space. Section VIII describes the suggested dynamic A-RFID MAC protocol. Section IX concludes the paper.

II. PASSIVE AND ACTIVE RFID

There are three main groups of RFID: P-RFID, A-RFID, and S-RFID (semi). The "semi" means that the tags are partly battery powered to assist a more complex processor core that boosts functionality compared to P-RFID.

The most common RFID technology today is P-RFID. The tags have no energy source of their own but instead they are powered by the reader's magnetic or electromagnetic field which is converted to electrical power by the tags [8, 9, 10]. Although this enables low-cost tags the main drawbacks are: 1) the limited working distance between reader and tag, 2) the high transmitted reader energy required; and 3) the fact that sensor readings and calculations are not possible when there is no reader in the vicinity to power the tags.

In A-RFID the working distance can be much longer (a few hundred meters). A-RFID tags, having their own power sources, can use higher transmit power and receivers with higher sensitivity. Another benefit is that sensor measurements, calculations, and storage are possible even when there is no reader in the vicinity of the tag. 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 (the reader powers the tags only from a short distance, typically a few decimeters). 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.

III. RELATED RESEARCH WORK ON A-RFID PROTOCOLS

There are several companies developing systems for A-RFID, but no agreement exists of a worldwide standard that fits a large variety of applications.

Research done by Bhanage et al. [11] to enable a power efficient reading protocol for A-RFID shows interesting results. Their idea is to reduce information sent in the network and also to reduce the energy used to detect collisions by enabling smart sequencing in real time. The Relay MAC protocol proposed yields better throughput and energy conservation than a conventional binary search protocol. The disadvantage of the Relay MAC protocol is that the reader coordinates the reading sequence, which means that when a load with new ID-tagged goods arrives at a reading spot the reading sequence has to be re-initialized.

An anti-collision algorithm for A-RFID, enabling increased power efficiency, is proposed by Li et al. [12]. The RFID-system uses two channels, one for data and one for control. Every tag starts by doing an exponential back-off and then starts to send. The reduced power consumption is explained to be due to the tag power-down-mode during the back-off. The authors report simulations with up to 20 tags, a rather small amount. They claim a life-time of five years when the battery capacity is 950 mAh and 100 readings are made per day. Nothing is mentioned about how many tags that were used in the A-RFID-system when achieving the five years of life-time.

An interesting way of reducing power is described by Chen et al. [13]. Instead of the tag waking up periodically, a sensor based wake up is used. Their experiments show that, with a sensor-enhanced active RFID system, the battery lasts twice as long in comparison to a system without any embedded sensors.

With focus on waking a tag by using low energy, Hall et al. [14] have constructed a "turn on circuit" in standard CMOS technology based on a Schottky barrier diode. Calculations of the usable "turn on" range (using a favorably oriented antenna with 6 dB of gain and an operating frequency of 915 MHz, and output power of 1W) gives a theoretical operating range of 117 m.

Shweta et al. [15] have developed a CSMA-based [16] MAC protocol to avoid collisions in a dense A-RFID network. Results from evaluations show that it has superior performance compared to a randomized protocol with regard to readability (probability that many readers read the same tag when the tag is in the vicinity of several readers at the same time) and time per tag read.

A stochastic anti-collision algorithm, the DFSA algorithm (Dynamic Framed Slotted ALOHA) is investigated by Leian et al. [17]. They show that, in a slotted ALOHA-based anti-collision RFID system, maximum throughput is achieved when the number of slots is the same as the number of tags. For estimation of the number of tags, two methods (based on a ternary feedback model) are presented and demonstrated.

A hybrid TDMA (Time Division Multiple Access) MAC protocol is proposed for A-RFID by Xie et al. [18]. The protocol is contention based for high density tag conditions. The tag contends, by using Rivest's Pseudo-Bayesian algorithm, to get a communication slot and then stays synchronized with the reader with the TDMA protocol.

Li et al. [19] suggest a DCMA (Dual Channel Multiple access) protocol for A-RFID where long information packets are used. One channel is used for control and the other for data. Thus, when new tags enter the system on the control channel, they will not collide with tags scheduled on the data channel. This is said to reduce the power consumption but the effect on delay or throughput of the A-RFID system is not reported.

For A-RFID systems using transmit-only tags, Mazurek [20] proposes a DS-CDMA (Direct Sequence Code Division Multiple Access) protocol to improve tag recognition rate. The tags do not need to be synchronized with the reader, which keeps the tag design simpler. Simulations show that the proposed DS-CDMA outperforms the classical narrow band Manchester-coded RFID/ALOHA when comparing probability of tag detection.

IV. THE A-RFID MAC PROTOCOL

The medium access protocol that we model in our study is a contention based non-persisting carrier sense multiple access protocol with collision avoidance (CSMA/CA) using a non-slotted channel, see Figure 2.

The reader initially awakes the tags when the tags come within range, using a beacon message. This message contains three parameters: 1) channel: what frequency the tag should transmit its payload on; 2) *ICW* (Initial Contention Window): the time period during which all tags must try to do their first transmission attempt; 3) a coefficient (explained later). The tag uses the information to select a stochastic (evenly distributed) initial back-off time (t_0, Figure 4) during the *ICW* and calculates the subsequent back-off times using the appropriate algorithm and coefficient. After the initial back-off time the tag performs a carrier sense (CS) to detect if any other tag is using the radio channel. If the channel is free the tag transmits its payload packet (200 data bits) and waits for an acknowledgement from the reader. If the channel is occupied the tag performs a new back-off. When the packet subsequently is successfully delivered to the reader, the reader transmits an acknowledge packet to the tag which then enters sleep mode.

The key feature in our A-RFID protocol is the possibility to adapt the back-off algorithm to different application scenarios. When tailoring an A-RFID protocol for different application scenarios we need to define the most important application constraints. These have been identified to be the energy efficiency, the message throughput and the read-out delay requirements. The read-out delay is the time taken from when the tag is addressed until it delivers the data.

Previous work [21] shows that the CS facility in IEEE 802.15.4, when used for A-RFID, increases the energy efficiency. The CS is used to avoid air collisions in the air interface. The key to achieving the above mentioned requirements is not only the CS, it is the combination of the CS and the used back-off scheme.

A. *Related Work on Back-off Algorithms*

Some research work has been published on how to achieve higher efficiency (fewer collisions on the radio channel) in the IEEE 802.11 standard by applying a back-off strategy. Taifour et al. [22] propose the 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.

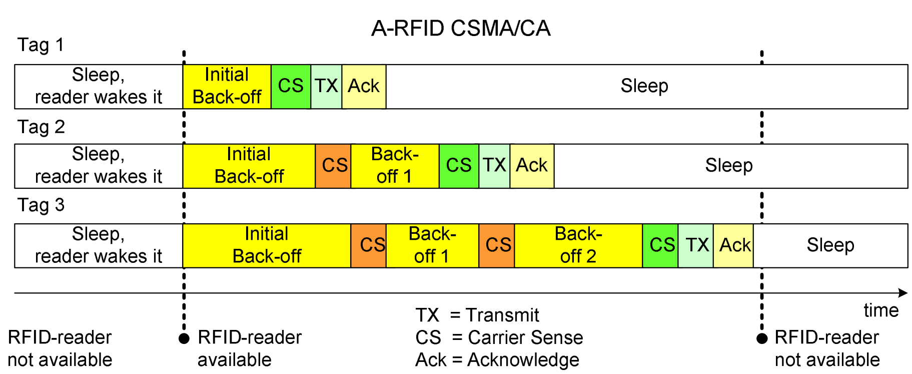

Figure 2. Tags delivering their payload packets to a reader.

Jayaparavathy et al. [23] suggest that the back-off time for each contending node can be modified by retrieving information obtained from transmitting stations (delay from the contending nodes) thereby getting higher throughput and shorter delays.

Bhandari et al. [24] 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. [25].

An alternative back-off policy, called the μ-law or the step function, can outperform the exponential back-off, as shown by Joseph et al. [26]. 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. [27], claiming 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.

The described related work on wireless networks is not directly adaptable to A-RFID due to its different nature. In A-RFID, short messages from a large amount of tags must be passed on to the reader with short delay and with very low energy consumption. The reader-tag communication does not establish a continuous communication link as in other wireless networks.

V. 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 in the model is ideal (transmission error-free, no fading, and not attenuated) and the radio signal propagation delay is neglected because of the short tag-reading distances. A transmission error only occurs when packets overlap each (in any fraction) other. The times for the transceiver to switch between the different states (TX, RX, CS) are neglected because these times typically are much shorter than the packet transmission time.

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 [28]. It has a working range of 50 m in free space. The maximum output power is 0 dBm (1 mW), the receiver sensitivity is –90 dBm, and the channel bandwidth is 1 MHz. Table I shows time duration and power requirements for the transceiver to do a CS, a TX (200 bits), and an Ack (200 bits).

TABLE I. TAG IN DIFFERENT STATES.

	Time[ms]	**Power**[mW]
CS	0.128	57.0
TX	1.6	42.0
Ack (RX)	2.0	57.0
Sleep	*vary*	0.011

B. *Simulation Method and Model*

All simulations are done using Matlab and begin with a population of 50 tags available to the reader. Simulations are then done for an increasing number of tags until reaching 1050. All tags are assumed to 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 simulation ends. Both the payload and the acknowledge packets are 200 bits long.

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. This is repeated 100 times, after which an average value is calculated.

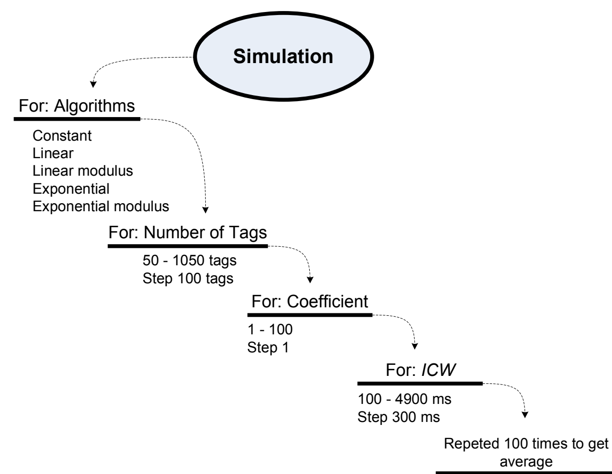

Figure 3. The simulation procedure.

Each tag makes a first initial random back-off in the *ICW*. On waking up, 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 4). 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). Hidden terminals (tags within range of the reader but out-of-range of each other) are handled via the ACK protocol used (the tag re-transmits its message until it receives an ACK from the reader, and then sleeps for the rest of the simulation).

C. The Back-off Algorithms

Through simulations, the energy consumption and read out delays incurred by the five different back-off algorithms and their back-off coefficients and Initial Contention Windows have been determined. The back-off algorithms simulated are: *constant* (1)*, linear* (2)*, linear modulus* (3)*, exponential* (4)*,* and *exponential modulus* (5). The equations below describe the five algorithms. The behaviors of the algorithms are depicted in Figure 4.

$$t_{i+1} = t_i + C \cdot T_{slot} \quad (1)$$

$$t_{i+1} = t_i + L \cdot i \cdot T_{slot} \quad (2)$$

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

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

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

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 Ack.

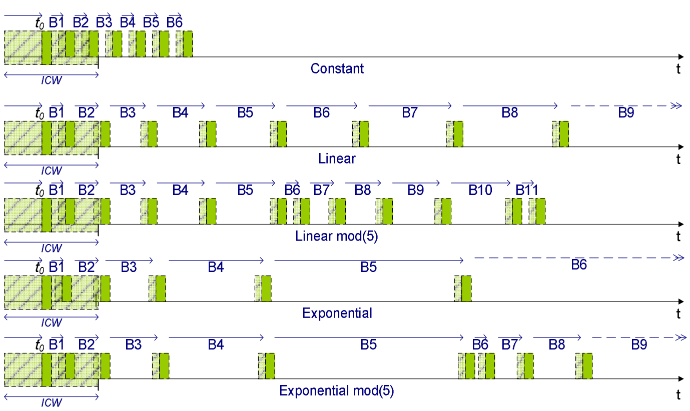

Figure 4. Types of back-off algorithms: constant, linear, linear modulus, exponential, and exponential modulus. The arrow ending at time t_o (randomly chosen by each tag in the range of the *ICW*) is the initial back-off, then increasing B-numbers show successive back-offs. Shadowed parts show randomness in the back-off time which is added to each T_i.

VI. 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 Figure 5 *Energy*, *Delay* and *EDP* are shown as a function of the number of tags and the coefficient for the constant algorithm. Both energy and delay also depend on the *ICW*, but this is not shown in the figure. Instead, the minimum values, when the *ICW* is varied, are presented, see equations (6), (7), and (8). The $Energy_S$ is the energy in average required by a tag 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.

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

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

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

Figure 5 shows results from simulation of the constant back-off time algorithm. The energy diagram of Figure 5 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 the coefficient C is small.

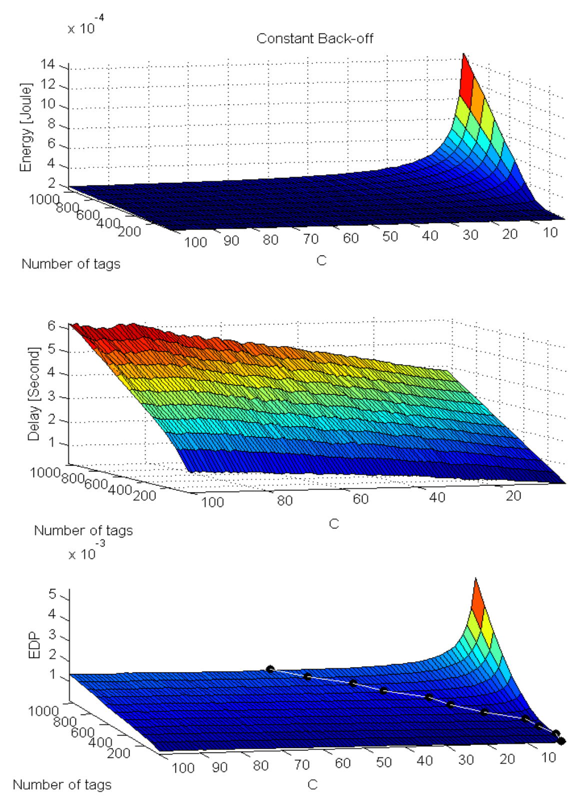

Figure 5. Simulation results for constant back-off time. min Energy Consumption (top), min Delay (middle), and Energy-Delay Product (bottom) as a function of the coefficient C, and the number of tags.

The middle diagram in Figure 5 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*.

To compare the algorithms 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 Figure 5. For each number of tags there also exists a minimum *EDP* (see 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.

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

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

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

To compare how the algorithms behave under varying loads an average *EDP* value has been calculated (11).
n is the incremental factor used to calculate the number of tags, and $EDP_{\min}$ is the lowest *EDP* possible with that number of tags.

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

The average EDP is shown in Table II. The data shows that four of the algorithms (const, lin, lin-mod, exp-mod), on average, perform similarly regarding the EDP metric. The exception is the exponential algorithm without modulus which shows a much higher average EDP value.

Figure 6 shows the situation when 850 tags are in the vicinity of the reader and using the constant algorithm. The left diagram shows the energy consumption and the right diagram shows the delay. As can be seen there is a tradeoff between energy consumption and delay. Decreasing one will increase the other and vice versa. The diagram to the left shows, as a line at the bottom of the diagram, the minimum energy consumption of a tag for the constant algorithm. The lines with small circles are the corresponding energy consumption values when the *ICW* has been chosen for the minimum delay. The diagram to the right shows the minimum delay (line with circles). In this diagram the plain line shows what the delays are when using the minimum energy.

TABLE II. AVERAGE EDP.

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

The conclusion is that one can choose to minimize with regard to energy consumption or delay or choose a compromise of both. After analyzing the simulation data for different numbers of tags, decisions can be made on how to tune the algorithm, the coefficient, and the *ICW* for a certain application. To achieve an energy efficient protocol one should dynamically select the coefficient as well as the *ICW*, depending on the application.

VII. EXPLORING THE DESIGN SPACE

For a specific application scenario, the appropriate *ICW* and coefficient must be identified. Table III shows, for the constant back-off algorithm, how to choose the *ICW* and the coefficient and how much energy is needed for a tag to transmit a payload packet to the reader. The table data are extracted from simulation results.

For example, assume that the application normally uses 250 tags and that they are in range of the reader for 3 seconds. In this case a delay of 2500 ms is chosen (nearest to 3 seconds and still not over 3 seconds), and the number of tags is chosen from the second column, 250 tags. Now the *ICW* is read out as 2500 ms and the coefficient is set to 2. The average energy consumption for a tag to transmit its payload is 186 μJ. The empty areas in the table represent situations where it is impossible to have all tags deliver their payload within the given time. The upper row also includes the minimum delay with that specific amount of tags. E.g. when there are 50 tags the minimum delay for all tags to deliver a payload is 211 ms. By observing the region near the empty area one can conclude that operating near minimum delay (read tags fast) increases the energy consumption.

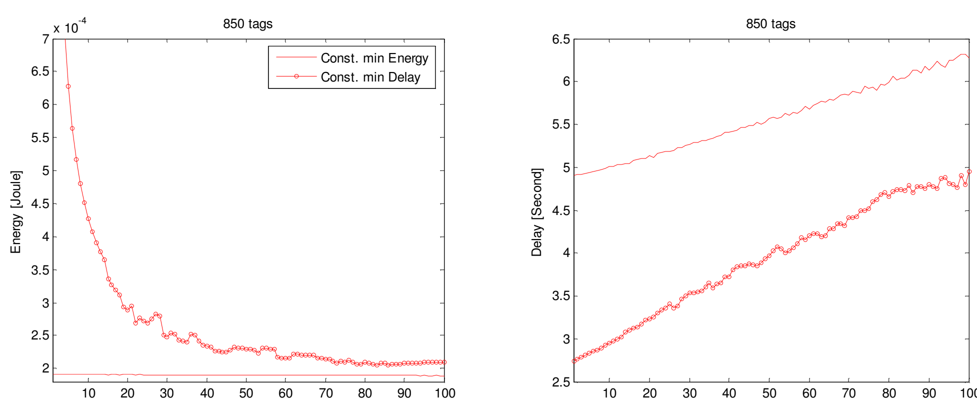

Figure 6. The energy-delay trade off in the case of 850 tags and the constant algorithm. Left graph: Energy consumption as a function of the back-off coefficient. Right graph: Delay as a functions of the back-off coefficient. Legend in both graphs: "lines with circles" show when the *ICW* has been selected in order to minimize the delay. The "plain" lines show when the *ICW* has been selected in order to minimize energy.

While Table III is only for one of the algorithms (constant) with varying number of tags, Table IV & V compare all the simulated algorithms but with the number of tags fixed to 50 and 1050, respectively. In the case of 50 tags and long delay (over 450 ms), Table IV shows that any of the algorithms can be chosen and that the energy consumption is the same for all. For short delays, less than 250 ms, only the constant and the linear modulus can be used.

VIII. THE SUGGESTED DYNAMIC A-RFID MAC PROTOCOL

The MAC protocol functions according to the protocol described in Figures 2 and 4. Tags in range of the reader are awakened by a broadcast message (a continuously repeated beacon signal) from the reader which includes what channel they should identify themselves on, and which coefficient and *ICW* to use.

As discussed in the previous section it is possible to choose one of the algorithms and still meet the delay and energy constraints. Tags then only need to implement, e.g., the constant algorithm. The reader adapts the coefficient and *ICW* based on known application context and on history information from previous read-outs. Should these values be too hard to extract (because, e.g., the number of tags is totally unpredictable) the worst-case parameters should be used (minimum delay and maximum number of tags). The appropriate values for the *ICW* and coefficient (C) for the constant back-off algorithm are then to be chosen dynamically from Table III (note that for RFID-systems where Table I values not are applicable, Table III values need to be regenerated).

To get the tag battery life time in days as functions of the number of tags and the required delay see Table VI. Assumed is a 3 Volt lithium tag battery (CR2032) with a capacity of 150 mAh. The energy values from table III are used. It is assumed that each tag delivers one payload packet once per minute. When a tag has delivered its payload it goes to sleep until the next read. The "sleep" power value from Table I is therefore added when calculating the energy values in Table VI. In the case when the tag stays in sleep all the time the battery will last for 1705 days. Table VI reveals that the tag battery lifetime varies from a minimum value of 961 days (450 tags, 1.7 seconds delay) to a maximum value of 1452 days (50 tags, 6 seconds delay).

TABLE VI. THE TABLE SHOWS HOW LIFETIME (DAYS) FOR A TAG VARIES WITH A CHOSEN DELAY AND DIFFERENT NUMBER OF TAGS.

	Tags		
Delay[ms]	50	450	1050
250	1300		
1700	1366	961	
4000	1410	1401	1112
6000	1452	1444	1417
∞	1705	1705	1705

TABLE III. THE *ICW* AND THE COEFFICIENT VALUES, C, GIVING LOWEST ENERGY CONSUMPTION (ENERGY) WHEN CHOOSING A SPECIFIC DELAY AND A SPECIFIC NUMBER OF TAGS FOR THE CONSTANT ALGORITHM.

	Number of tags (Constant)					
Delay[ms]	50 (MinDelay=211ms)	250 (MinDelay=935ms)	450 (MinDelay=1659ms)	650 (MinDelay=2381ms)	850 (MinDelay=3103ms)	1050 (MinDelay=3825ms)
250	***ICW***=100ms **C**=4 **Energy**=208µJ					
500	400ms 13 186µJ					
1000	1000ms 1 182µJ	400ms 3 324µJ				
1700	1600ms 35 182µJ	1600ms 10 191µJ	1000ms 1 529µJ			
2500	2500ms 40 182µJ	2500ms 2 186µJ	2200ms 13 199µJ	2200ms 1 348µJ		
3200	3100ms 17 182µJ	3100ms 26 184µJ	3100ms 11 190µJ	3100ms 4 203µJ	2200ms 2 521µJ	
4000	4000ms 75 182µJ	4000ms 4 183µJ	4000ms 1 187µJ	3700ms 20 194µJ	3700ms 10 211µJ	3400ms 2 394µJ
5000	4900ms 19 181µJ	4900ms 2 183µJ	4900ms 17 185µJ	4900ms 12 188µJ	4900ms 6 194µJ	4900ms 4 207µJ
6000	4900ms 19 181µJ	4900ms 2 183µJ	4900ms 99 185µJ	4900ms 93 187µJ	4900ms 67 192µJ	4900ms 42 200µJ

TABLE IV & V. THE *ICW* AND THE COEFFICIENT VALUES, C, L, AND E, GIVING LOWEST ENERGY CONSUMPTION (ENERGY) WHEN CHOOSING A SPECIFIC DELAY, 50 AND 1050 TAGS, AND THE DIFFERENT ALGORITHMS.

	50 Tags				
Delay[ms]	Constant (MinDelay=211ms)	Linear (MinDelay=279ms)	Linear modulus (MinDelay=225ms)	Exponential (MinDelay=450ms)	Exponential modulus (MinDelay=276ms)
211	***ICW***=100ms **C**=1 **Energy**=236µJ				
225	100ms 2 221µJ		***ICW***=100ms **L**=1 **Energy**=220µJ		
279	100ms 6 203µJ	***ICW***=100ms **L**=1 **Energy**=209µJ	100ms 3 202µJ		***ICW***=100ms **E**=1 **Energy**=203µJ
450	400ms 8 186µJ	400ms 4 186µJ	400ms 5 186µJ	***ICW***=400ms **E**=1 **Energy**=186µJ	400ms 1 187µJ
1000	1000ms 1 183µJ	1000ms 3 183µJ	1000ms 1 183µJ	1000ms 1 183µJ	1000ms 3 183µJ
2000	1900ms 15 182µJ	1900ms 20 182µJ	1900ms 31 182µJ	1900ms 12 183µJ	1900ms 35 182µJ
3000	2800ms 73 182µJ	2800ms 96 182µJ	2800ms 82 182µJ	2800ms 147 182µJ	2800ms 50 182µJ
6000	4900ms 19 181µJ	4300ms 4 181µJ	4900ms 79 181µJ	4900ms 11 181µJ	4900ms 74 181µJ
	1050 Tags				
Delay[ms]	Constant (MinDelay=3825ms)	Linear (MinDelay=4487ms)	Linear modulus (MinDelay=3850ms)	Exponential (MinDelay=19467ms)	Exponential modulus (MinDelay=3947ms)
3825	***ICW***=100ms **C**=1 **Energy**=2052µJ				
3850	1600ms 1 1312µJ		***ICW***=100ms **L**=1 **Energy**=1431µJ		
3947	3400ms 1 477µJ		2800ms 1 568µJ		***ICW***=400ms **E**=1 **Energy**=667µJ
4487	4300ms 4 228µJ	***ICW***=3100ms **L**=1 **Energy**=269µJ	4300ms 2 228µJ		3700ms 2 240µJ
5000	4900ms 4 207µJ	4600ms 1 212µJ	4900ms 2 206µJ		4600ms 2 209µJ
6000	4900ms 42 200µJ	4900ms 9 199µJ	4900ms 25 198µJ		4900ms 8 198µJ
7000	4900ms 91 195µJ	4900ms 22 196µJ	4900ms 53 194µJ		4900ms 18 195µJ
19467	4900ms 98 195µJ	4900ms 100 191µJ	4900ms 100 191µJ	***ICW***=4900ms **E**=37 **Energy**=191µJ	4900ms 100 189µJ

IX. CONCLUSIONS

The need for an active (A-RFID) protocol that addresses and supports a variety of application scenarios with different requirements on energy and read-out delays has initiated this work. The key feature in our A-RFID protocol is the possibility to dynamically adapt the back-off algorithm to different application scenarios.

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. By adaptively choosing the initial contention window size and the back-off coefficient it is possible to adapt to different RFID application scenarios.

The proposed method of using a dynamic, instead of a non-dynamic, back-off scheme results in lowered average tag power consumption (increased tag battery life time). A non-dynamic scheme would need to utilize worst-case parameters, yielding the highest power consumption values in all scenarios.

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