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Research Article

An Energy and Application Scenario Aware Active RFID Protocol

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The communication protocol used is a key issue in order to make the most of the advantages of active RFID technologies. In this paper we introduce a carrier sense medium access data communication protocol that dynamically adjusts its back-off algorithm to best suit the actual application at hand. Based on a simulation study of the effect on tag energy cost, read-out delay, and message throughput incurred by some typical back-off algorithms in a CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance) active 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 show that it is possible to decrease the energy consumption per tag payload delivery with more than 10 times, resulting in a 50% increase in tag battery lifetime. We also discuss the advantage of being able to predict the number of tags present at the RFID-reader as well as ways of doing it.

1. Introduction

1.1. Background. Emerging technologies, like printed batteries and the continuous advancements in CMOS-ASIC (Complementary Metal Oxide Semiconductor-Application Specific Integrated Circuit) fabrication and antenna technologies, cast new exciting light onto the established technology of Radio Frequency IDentification (RFID). The mentioned developments have made it possible to expand the usage of RFID and narrow the span between different flavors of RFID technologies. 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 two main categories, passive RFID and active RFID. This work investigates the possibilities of defining an active RFID protocol that is paving the way for different applications without deteriorating the performance regarding tag lifetime and read-out delays. We argue that, for this to be possible, the protocol must be adaptable to the specific application scenario at hand. In a previous paper [1] we have introduced such a protocol and demonstrated the possible gains in tag energy consumption and read-out delay. In the current paper we first show the great advantages of using carrier sense; we then review the principle and design of the adaptable protocol, and finally present how to get maximum advantage of such a protocol.

1.2. Paper Outline. The outline of this paper is as follows. In Section 2, RFID systems and related research work are presented, and in Section 3 we show the impact of using carrier sense in active RFID protocols. Section 4 introduces the suggested, application sensitive, active RFID protocol which is built on the idea of adaptively choosing the best back-off algorithm parameters. Section 5 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 6 shows simulation results. Section 7 shows optimization in regards to the delay or to the power consumption. Section 8 explores the design space. Section 9 describes the suggested dynamic active RFID Medium Access Control (MAC) protocol. In Section 10 we discuss different ways of estimating the number of tags in an active RFID scenario as an introduction to future work. Section 11 concludes the paper.

2. RFID Systems

2.1. RFID Application Scenarios. Automation in logistics has driven the development of RFID in the past years. Scenarios for RFID [2] appear, for instance, in the logistics chain, tracking goods from the producer to the consumer, depicted in Figure 1, where the goods can be one single product or up to several hundred products on a single pallet; see Figure 2. Items must be identified with short delay by the RFID-reader when, for example, they are passing an RFID-reader on a vehicle with high speed. In this realm, RFID could also be used for automatic inventory of the stock in a warehouse, where the reading delay is not critical but where there is a huge amount of tagged goods to identify.

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 a scenario with a fork lift passing the reader closely needs only a small amount of radiated energy, due to the short distance, but needs fast readings due to the high vehicle velocity. For a scenario with a large warehouse, and thus long distances, the reader needs to radiate higher amount of energy—unless many RFID-readers are deployed, yielding the well-known drawback with the "multi-reader problem" which deteriorates readability; however this scenario has no hard read-out time requirements.

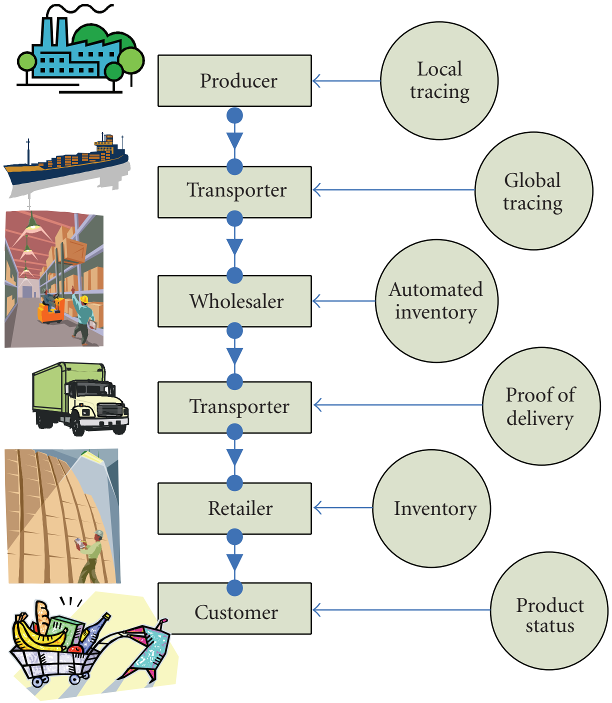


FIGURE 1: Logistics chain supervision.

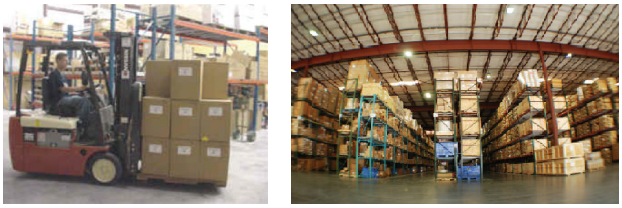


FIGURE 2: Different application scenarios requiring different read-out delay and throughput to be efficient.

2.2. Passive and Active RFID. There are three main types of RFID: passive RFID, active RFID, and semi-RFID. The "semi" means that the tags are partly battery powered to assist a more complex processor core that boosts functionality compared to passive RFID.

The most common RFID technology today is passive RFID. The tags have no energy source of their own; instead they are powered by the reader's magnetic or electromagnetic field which is converted to electrical power. 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 active RFID the working distance can be much longer (a few hundred meters, set by the link budget). Active RFID tags, having their own power sources, can use higher transmit power and receivers with higher sensitivity. Other benefits are sensor measurements, complex calculations, and storage 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 passive RFID (the reader powers the tags only from a short distance, typically a few decimeters). Active 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.

2.3. Today's Standards and Protocols. Much work has been done for standardization of passive RFID, such as the EPCglobal standards development [3]. The majority of active RFID protocols are proprietary. However, some existing standards used in WLAN and Zigbee are currently being used in active RFID applications despite their disadvantages regarding tag price and battery life-time [4].

The standard ISO 18000-7 [5] defines the air interface for a device acting as an active tag. Its purpose is to provide a common technical specification for active RFID devices. 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.

The lack of research work related to active RFID protocols raises some important research questions; one is how to design energy efficient protocols for active RFID. Some related research has been done in the wireless network field, with the aim of not only to reduce energy cost but also to increase throughput and minimize read-out delay. However, this is not directly applicable to active RFID due to its different nature (this is further elaborated on in Section 4.1). Protocol design should address the different needs for the different applications scenarios. Some application, needs short read-out delays but some do not; having this in mind when designing the protocol, it is possible to reduce the tag power consumption and thereby increase tag battery life-time.

2.4. Related Research Work on Active RFID Protocols. There are several companies developing systems for active RFID, but no agreement exists of a worldwide standard that fits a large variety of applications scenarios.

Research done by Bhanage and Zhang [8] to enable a power efficient reading protocol for active 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 reinitialized.

Li et al. [9] suggest a DCMA (Dual Channel Multiple access) protocol for active 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 active RFID system is not reported. 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 use of a control channel and 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 active RFID-system when achieving the five years of life-time.

An interesting way of reducing power is described by Chen et al. [10]. 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. [11] 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 an operating frequency of 915 MHz, and output power of 1 W) give a theoretical operating range of 117 m.

Jain and Das [12] have developed a CSMA-based (Carrier Sense Multiple Access) MAC protocol [13] to avoid collisions in a dense active 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 anticollision algorithm, the DFSA algorithm (Dynamic Framed Slotted ALOHA) is investigated by Leian and Shengli [14]. They show that, in a slotted ALOHA-based anticollision 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 active RFID by Xie and Lai [15]. 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.

For active RFID systems using transmit-only tags, Mazurek [16] 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.

3. Active RFID and Carrier Sense

Carrier sense (CS) is used to avoid collisions in the radio channel. Using the carrier sense functionality has an advantage as long as the energy consumption for the sense action is held low. Simulation results [17] depicted in Figures 3, 4, and 5 show comparisons between using and not using CS in the same type of tag transmit first ALOHA protocol. For instance, in Figure 3 the CS protocol has 2.3 times higher throughput when there are 400 tags and 5 times higher throughput in the case of 1000 tags. Every tag wakes up during a cycle (the cycle time is set to one second in this case), at a time which has a uniform random distribution. The CS protocol, which is the top curve in Figure 3, shows highest throughput and heads towards maximum channel utilization (which theoretically is 556 tags/second). The throughput would of course decrease if propagation delays increase (and are of great magnitude) as shown by Rom and Sidi [13]. In this simulation the propagation delay is set to zero but for real cases it is less than 200 nanosecond and is a small fractional part of the CS (128 microsecond), resulting in a very low impact on the propagation delay.

Figure 4 shows the average delay until all tags have delivered at least one payload each (every tag delivers its payload periodically). The CS protocol shows good results even with a dense tag population (3000 tags). The curve for the protocol not using the CS raises rather quickly, resulting in a long delay already when only a small amount of tags are in the proximity of the reader. Repeating the CS until the channel becomes free consumes less energy than having to retransmit the payload if collision occurs. The expected

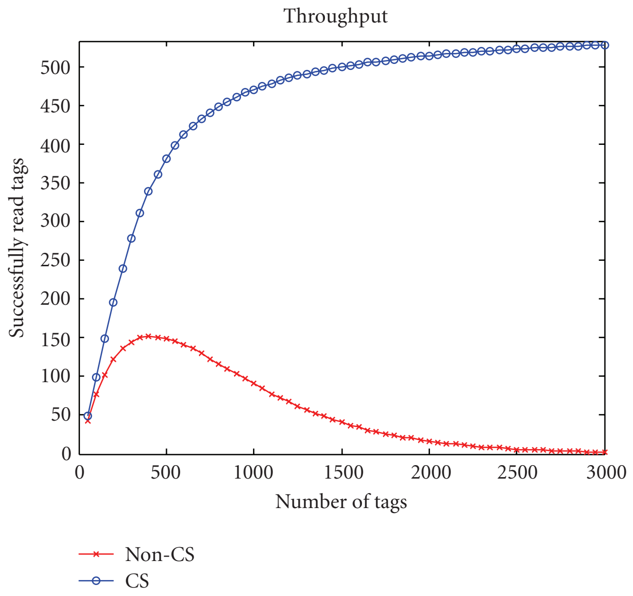


FIGURE 3: Throughput: number of tags read per second.

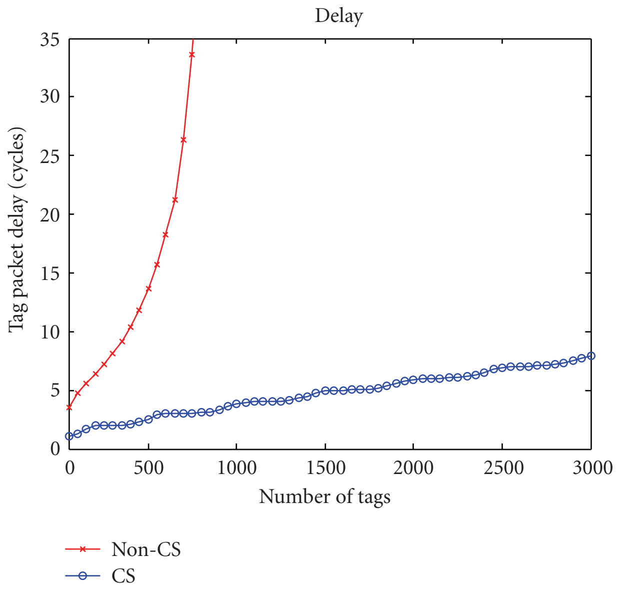


FIGURE 4: Delay: average time to read all available tags (the cycle time is set to 1 second).

lifetime, presented in Figure 5, reveals the much lowered energy consumption when using CS.

4. The Adaptive Protocol

The medium access protocol modeled in our study is a contention-based nonpersisting carrier sense multiple access protocol with collision avoidance (CSMA/CA) using a nonslotted channel; see Figure 6. It supports both cyclic awakening RFID systems as well as wake-up radio based. (A cyclic awakening system is when the tags wake up periodically trying to deliver their payload regardless if there is an RFID reader or not. The wake-up radio-based tags are equipped with a circuit that can sense if there is an available RFID-reader and thus know when to deliver its payload.)

The reader continuously broadcasts messages containing 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; and (3) a coefficient (explained later). The tag uses the information to select a stochastically evenly distributed initial back-off time (t_0, Figure 8) 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 the radio channel is free to use. If the channel is occupied, the tag performs a new back-off. Eventually the data packet (200 data bits) will be successfully delivered to the reader, and the tag enters sleep mode.

The key feature in our active RFID protocol is the possibility to adapt the back-off algorithm to different application scenarios. When tailoring an active RFID protocol for different application scenarios we need to define the most important application constraints. These have been identified to be the energy consumption, 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 its data.

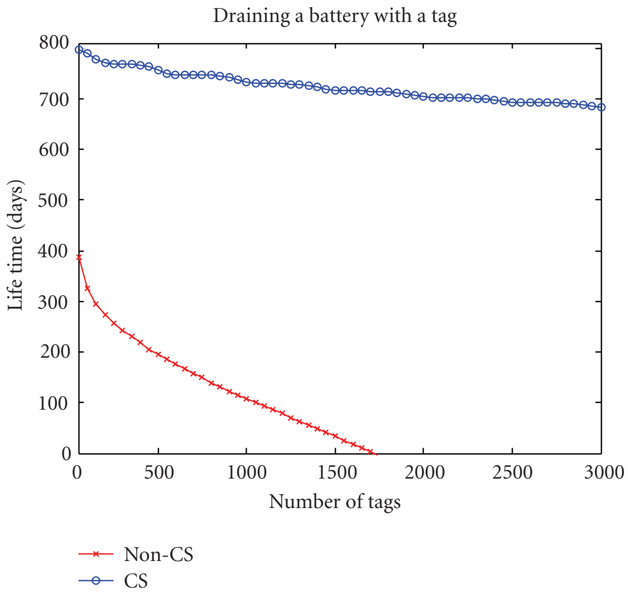


FIGURE 5: Lifetime of a tag powered CR2032 (150 mAh) lithium cell. The non-CS curve is extrapolated above 800 tags.

4.1. Related Work on Back-Off Algorithms in Wireless Networks. 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 different back-off strategies.

Taifour et al. [18] propose the neighborhood back-off algorithm (NBA) where the initial back-off interval

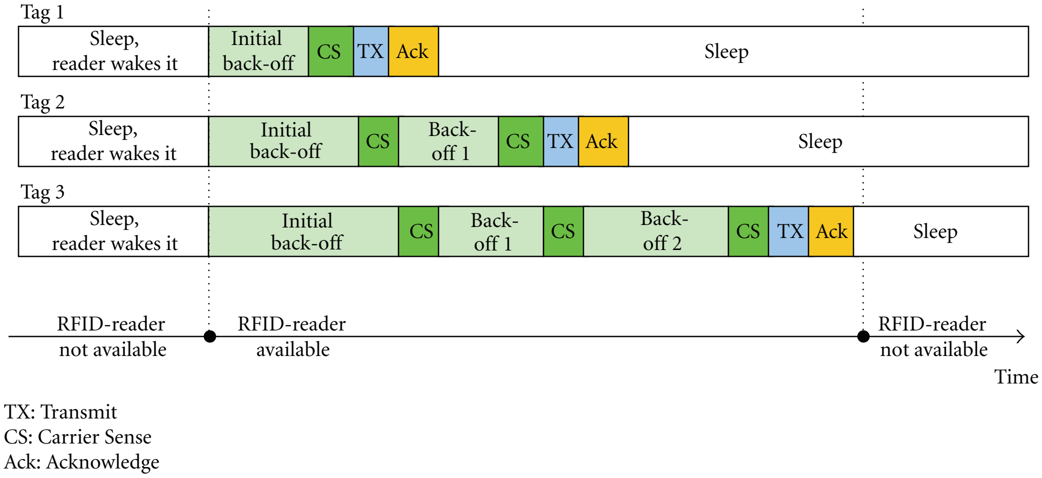


FIGURE 6: Tags delivering their payload packets to a reader.

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.

Jayaparavathy et al. [19] 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. [20] present simulation results that show that, by using binary slotted exponential back-off, the throughput and delay are 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. [21].

An alternative back-off policy, called the μ-law or the step function, can outperform the exponential back-off, as shown by Joseph and Raychaudhuri [22]. 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. [23], 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 active RFID due to its different nature. In active RFID, short messages from a large number of tags must be passed on to the reader with short delay and with very low energy consumption. The reader-tag communication does not need to establish a continuous communication link as in other wireless networks.

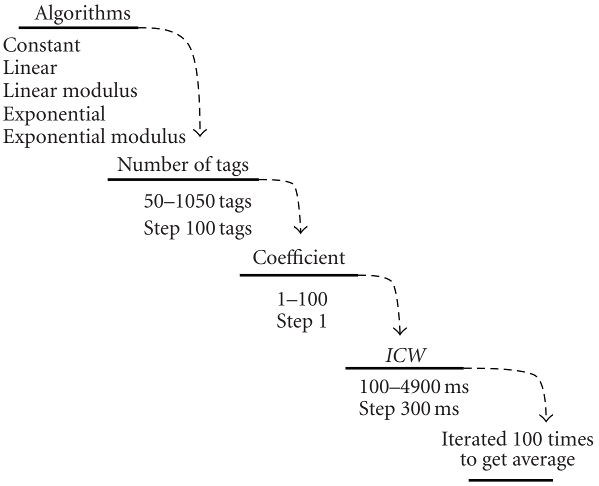


FIGURE 7: The simulation procedure.

5. Simulation Setup

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

5.1. Radio Channel Model. The radio channel model used 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 other (in any fraction) and there is no benefit from the capture effect. (When two or more nodes contend for the radio channel and transmit during the same time, the capture effect is that, instead of losing both data packages, there will be one node succeeding in delivering its payload packet.)

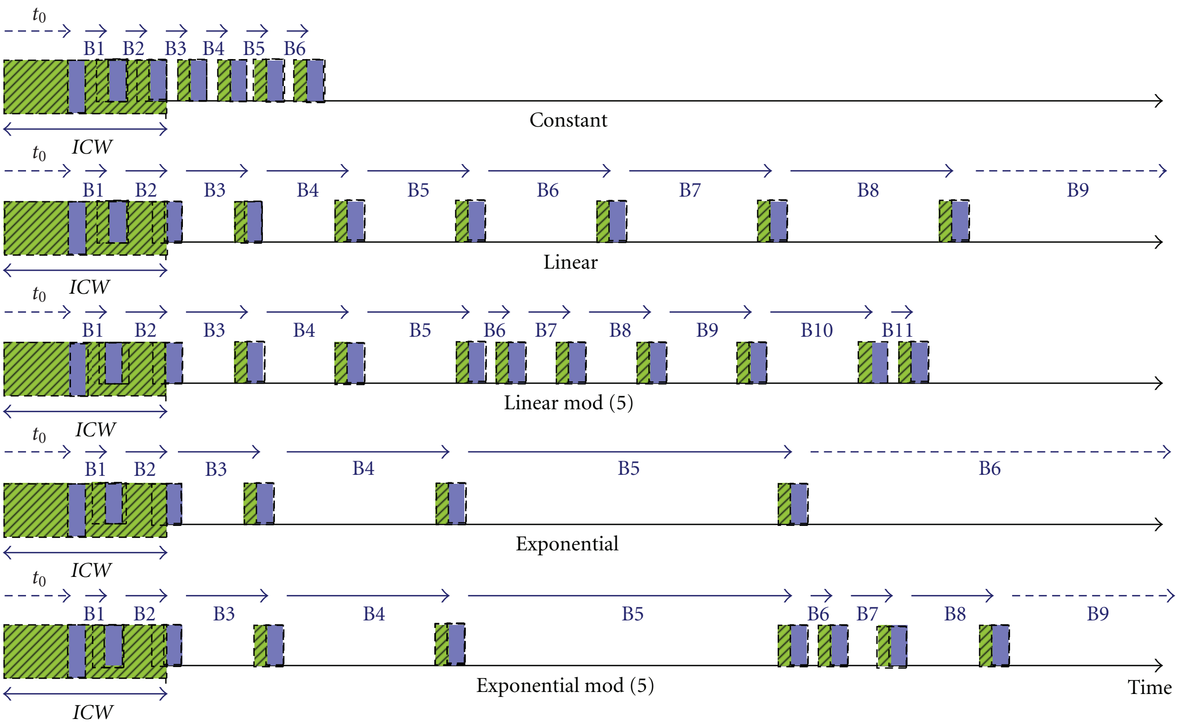


FIGURE 8: Types of back-off algorithms: constant, linear, linear modulus, exponential, and exponential modulus. The arrow ending at time t_o (randomly chosen by each tag in the range of the *ICW*) is the initial back-off, then increasing B-numbers show successive back-offs. Shadowed parts show randomness in the back-off time which is added to each T_i.

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 active RFID system modeled is built using the physical constraints of a commercially available transceiver [24] working in the 2.45 GHz ISM band with a bit rate of 250 kbit/second. It has a working range of more than 50 m calculated with free space propagation attenuation. The maximum output power is 0 dBm, the receiver sensitivity is −90 dBm, and the channel bandwidth is 1 MHz. Table 1 shows power and time requirements for the transceiver to do a CS, a TX (200 bits), and an ACK (200 bits).

5.2. 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. Figure 7 depicts the simulation procedure.

5.3. The Back-Off Algorithms. The back-off algorithms simulated are: *constant* (1), *linear* (2), *linear modulus* (3), *exponential* (4), and *exponential modulus* (5). The following equations describe the five algorithms. The behaviors of the algorithms are depicted in Figure 8:

TABLE 1: Power and time constraints when the tag is in different states.

Mode	Power consumption [mW]	Duration (ms)
Carrier Sense	57.0	0.128
Transmit	42.0	1.6
Receiving an ACK	57.0	2.0
Sleep	0.011	varies

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

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

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

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

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

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

Table 2: Average *EDP*.

Algorithm	Average *EDP* (m Joule Second)
Constant	0.61
Linear	0.67
Linear modulus	0.60
Exponential	5.00
Exponential modulus	0.60

(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.

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 milliseconds to 4900 ms in steps of 300 ms. 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.

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 8). This randomness is a time between 0 and 7.2 milliseconds (which is the time to do two RXs and two TXs 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 retransmits its message until it receives an ACK from the reader and then sleeps for the rest of the simulation).

6. Results

Applications using active 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*).

6.1. Energy, Delay and EDP.

6.1. 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* = Energy × Delay) [1, 25], a "goodness" value used for overall comparison of algorithms.

In Figures 9, 10, 11, 12 and 13 Energy, Delay, and *EDP* are shown as a function of the number of tags and the coefficient for the different algorithms. 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 (6). 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:

$$\begin{gathered}\text{Energy}(\#\,\text{tags}, \text{coeff}) = \min_{ICW} \text{Energy}_S(\#\,\text{tags}, \text{coeff}, ICW),\\ \text{Delay}(\#\,\text{tags}, \text{coeff}) = \min_{ICW} \text{Delay}_S(\#\,\text{tags}, \text{coeff}, ICW),\\ EDP_S(\#\,\text{tags}, \text{coeff}, ICW) = \text{Delay}_S \cdot \text{Energy}_S.\end{gathered} \tag{6}$$

Figure 9 shows results from simulation of the constant back-off algorithm. The energy diagram of Figure 9 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 9(b) 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*, (7), is the minimum of the product of energy and delay for each number of tags and each coefficient when varying the *ICW*, shown in Figures 9(c), 10(c), 11(c), 12(c) and 13(c). For each number of tags there also exists a minimum *EDP* (8) 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 $C = 15$:

$$EDP\ (\#\,\text{tags}, \text{coeff}) = \min_{ICW} EDP_S\ (\#\,\text{tags}, \text{coeff}, ICW), \tag{7}$$

$$EDP_{\min}(\#\,\text{tags}) = \min_{\text{coeff}} EDP(\#\,\text{tags}, \text{coeff}). \tag{8}$$

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

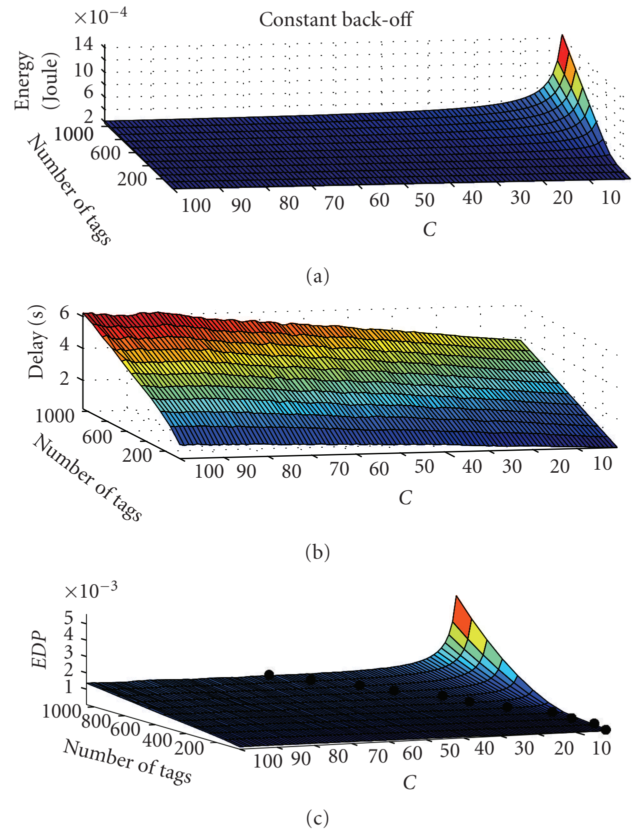
To compare how the algorithms behave under varying loads an average *EDP* value has been calculated (9). n is the incremental factor used to calculate the number of tags, and $EDP_{\min}$ is the lowest *EDP* possible with that number of tags:

$$\text{Avr}EDP = \frac{\sum_{n=0}^{10} EDP_{\min}(n \cdot 100 + 50)}{11}. \tag{9}$$

The average *EDP* is shown in Table 2. The data shows that four of the algorithms (const, lin, lin-mod, exp-mod), on average, perform similarly regarding the average *EDP* metric. The exception is the exponential algorithm without modulus which shows a much higher value.

7. Optimization

The key feature in our active RFID protocol is the possibility to adapt the back-off algorithm to different application scenarios. When tailoring an active RFID protocol for different



(a)

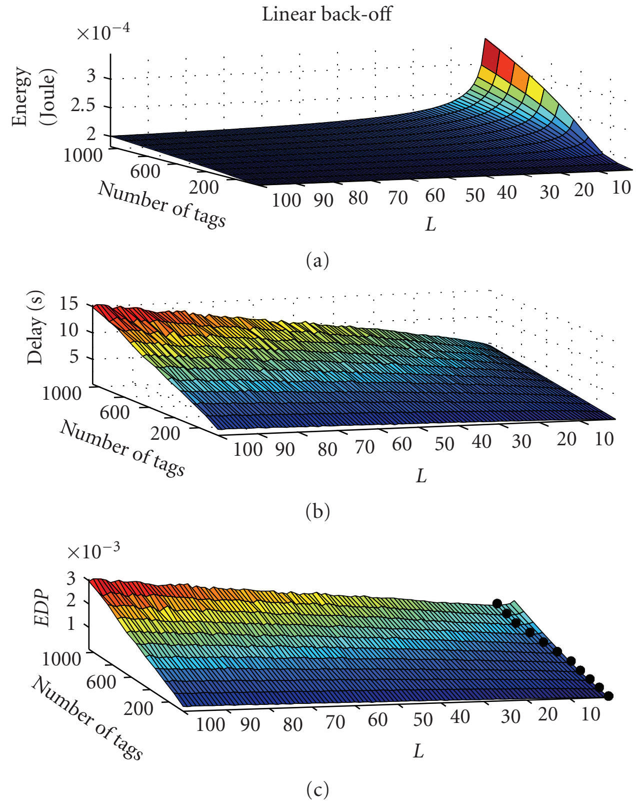
(b)

(c)

Figure 9: Simulation results for constant back-off time: min Energy Consumption (a), min Delay (b), and Energy-Delay Product (c) as a function of the coefficient C, and the number of tags.

application scenarios we need to define the most important application constraints. These have been identified to be the energy consumption, 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.

Applications using active 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. Conclusions show that it is possible to implement only one of the proposed algorithms by choosing the appropriate *ICW* and the appropriate constant to be able to adapt to different application constraints. Figure 14 shows the situation when 850 tags are in the vicinity of the reader and using the constant algorithm. The figure shows that there is a trade-off between delay and energy consumption by changing the coefficient and the *ICW*. Figure 14(a) 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. Figure 14(b) shows the minimum delay (line with circles). In this diagram the plain line shows what the delays are when using the minimum energy.

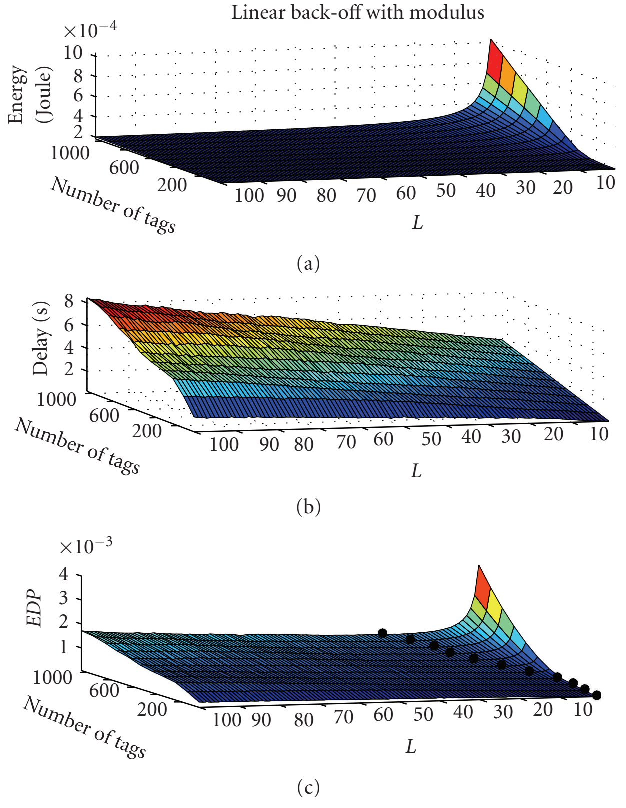


(a)

(b)

(c)

Figure 10: Linear back-off algorithm.

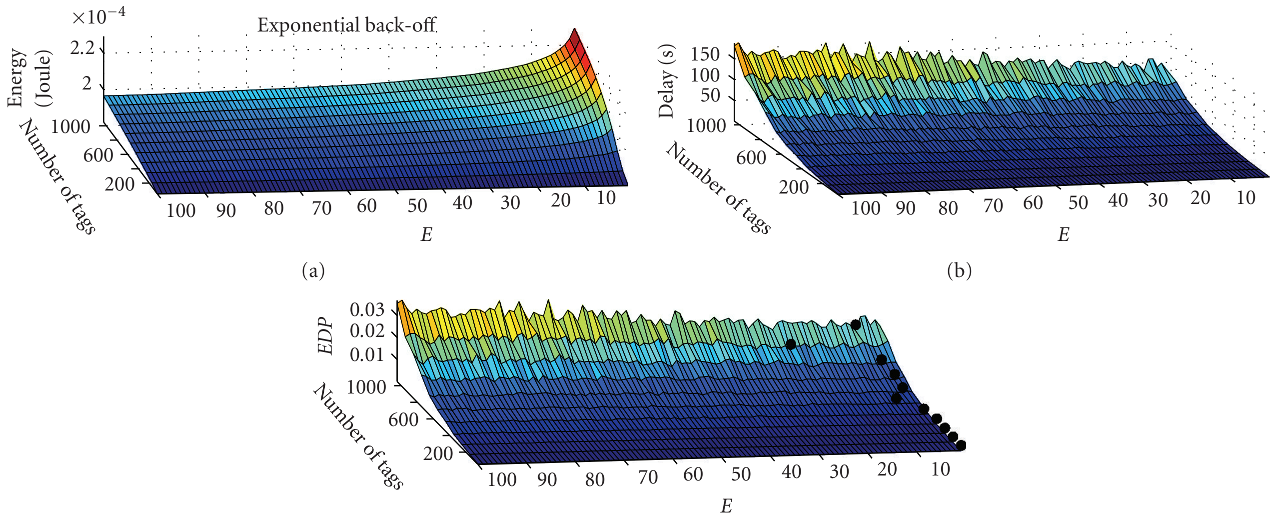


(a)

(b)

(c)

Figure 11: Linear back-off algorithm with modulus.

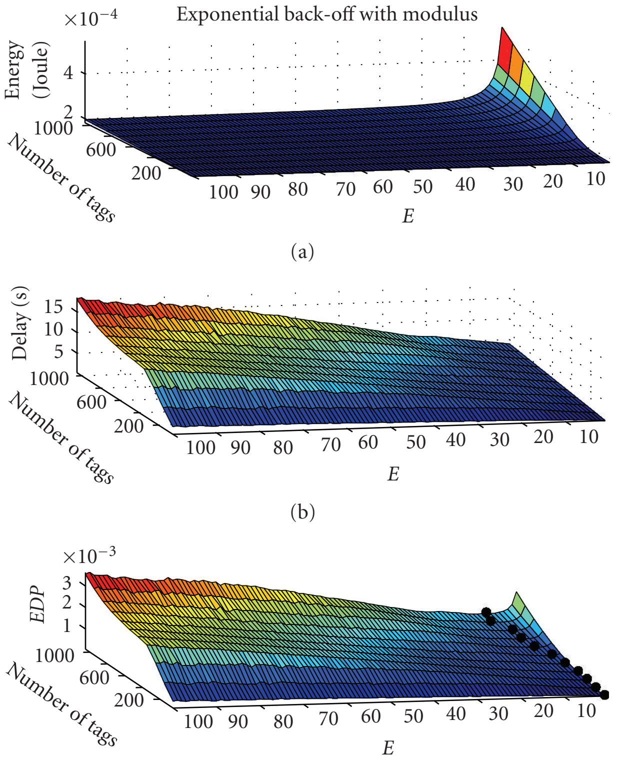


(a) (b)

(c)

Figure 12: Exponential back-off algorithm.

It is shown that minimizing the delay will increase the energy consumption by more than 8 times, and that minimizing the energy consumption will increase the delay by 2.3 times. The conclusion is that one can choose to minimize with regard to energy consumption or delay or find a compromise. To achieve an energy efficient protocol one should dynamically select the coefficient as well as the *ICW*, depending on the application scenario.



(a)

(b)

(c)

Figure 13: Exponential back-off algorithm with modulus.

8. Exploring the Design Space

For a specific application scenario, the appropriate *ICW* and coefficient must be identified. Table 3 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 is 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. For example, 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.

While Table 3 is only for one of the algorithms (constant) with varying number of tags, Tables 4 and 5 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 4 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.

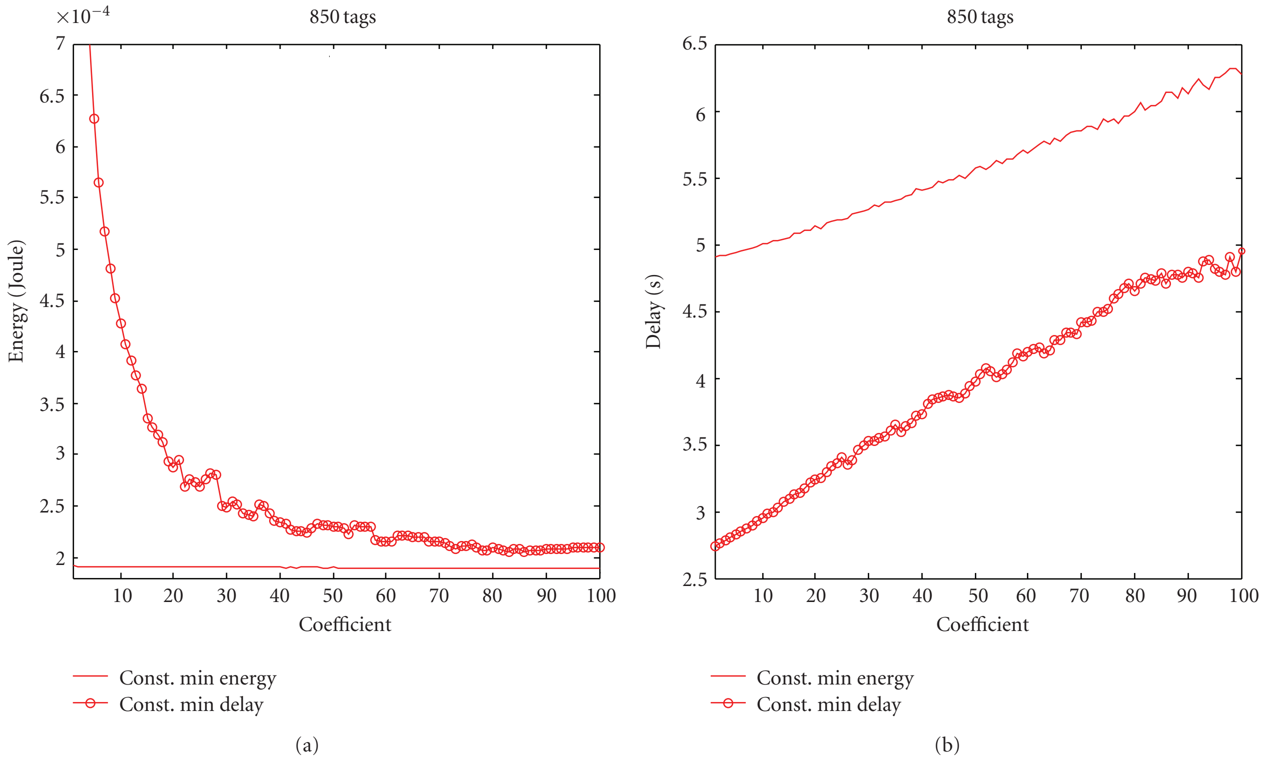


FIGURE 14: The energy-delay trade off in the case of 850 tags and the constant algorithm. (a): Energy consumption as a function of the back-off coefficient. (b): Delay as a functions of the back-off coefficient. "Lines with circles" show when the *ICW* has been selected in order to minimize the delay. The "plain" lines show when the *ICW* has been selected in order to minimize energy.

From Table 5 it is possible to extract information on how much better it is to use an adaptive protocol compared to a non-adaptive. If not using an adaptive protocol the worst case scenario has to be assumed, which is when there are a vast number of tags that need to be read fast (column 1 at a read-out delay of 3825 ms giving us an energy consumption of 2052 μJ). If the application accepts a longer read-out delay it is possible to adapt the protocol and save energy. Relaxing the constraint on the read-out delay to 7000 ms gives an energy consumption of 195 μJ, thus decreasing the energy consumption per tag payload delivery more than 10 times.

9. The Suggested Dynamic Active RFID MAC Protocol

The MAC protocol functions according to the protocol described in Figures 6 and 8. 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, for example, 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 3 (note that for RFID-systems where Table 1 values not are applicable, Tables 3–5 values need to be regenerated).

To obtain the tag battery life time in days as functions of the number of tags and the required delay see Table 6. Assumed is a 3-Volt lithium tag battery (CR2032) with a capacity of 150 mAh. The energy values from Table 3 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 1 is therefore added when calculating the energy values in Table 6. In the case when the tag stays in sleep all the time the battery will last for 1705 days. Table 6 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). To adaptively be able to choose protocol parameters, Table 6 shows that the lifetime can be increased by more than 50%.

10. Estimating the Number of Tags

The variety of application scenarios in which RFID can be used are limited only by imagination. However, defining

Table 3: 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.

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

a protocol that is energy and performance efficient over the entire imagination space seems to be a nonimaginable task. In order to use a protocol that can adapt to the application scenarios at hand we need information that characterizes the current circumstances and requirements.

As mentioned earlier, one issue is to predict the number of tags available to the RFID-reader. For applications where the number of tags is highly predictable, statistic calculations can be used, for example, a normal distribution averaging (over time) window. Kheiri et al. [26] use a method where they, by reading tags during a period of time can estimate the total number of tags. The method used to model the number of tags is inter-arrival times for a renewal process. This could be applicable to our proposed back-off protocol.

A method suggested by Floerkemeier [27] shows good performance compared to existing approaches by predicting the tag population using Bayesian broadcast strategies. The transmission control scheme is based on framed ALOHA and makes no restrictive assumption about the distribution of the number of tags close to the reader.

Applications in which the number of tags seems to be totally unpredictable are of course particularly challenging. One way to handle those cases, and possibly all cases, is to use information in databases, possibly several connected ones. The databases that typically already exist in the distribution chain contribute as a usable source of information for the RFID-readers. Figure 15 shows how a possible distribution flow could look like and where the readers could be placed. An RFID-reader that reads a tag can use the tag ID to get other specific information from a database. Useful information could be whether the specific tag that was read is in a batch of tags and, if so, how many tags were in that batch. In this way it is possible to know how to choose the protocol parameters to optimize for energy consumption or

Table 4: The ICW and the coefficient values, C, L, and E, giving lowest energy consumption (Energy) when choosing a specific delay, 50 tags, and the different algorithms.

	50 Tags				
Delay (ms)	Constant (Min delay = 211 ms)	Linear (Min delay = 279 ms)	Linear modulus (Min delay = 225 ms)	Exponential (Min delay = 450 ms)	Exponential modulus (Min delay = 276 ms)
211	$ICW = 100$ ms $C = 1$ Energy = 236 μJ				
225	100 ms 2 221 μJ		$ICW = 100$ ms $L = 1$ Energy = 220 μJ		
279	100 ms 6 203 μJ	$ICW = 100$ ms $L = 1$ Energy = 209 μJ	100 ms 3 202 μJ		$ICW = 100$ ms $E = 1$ Energy = 203 μJ
450	400 ms 8 186 μJ	400 ms 4 186 μJ	400 ms 5 186 μJ	$ICW = 400$ ms $E = 1$ Energy = 186 μJ	400 ms 1 187 μJ
1000	1000 ms 1 183 μJ	1000 ms 3 183 μJ	1000 ms 1 183 μJ	1000 ms 1 183 μJ	1000 ms 3 183 μJ
2000	1900 ms 15 182 μJ	1900 ms 20 182 μJ	1900 ms 31 182 μJ	1900 ms 12 183 μJ	1900 ms 35 182 μJ
3000	2800 ms 73 182 μJ	2800 ms 96 182 μJ	2800 ms 82 182 μJ	2800 ms 147 182 μJ	2800 ms 50 182 μJ
6000	4900 ms 19 181 μJ	4300 ms 4 181 μJ	4900 ms 79 181 μJ	4900 ms 11 181 μJ	4900 ms 74 181 μJ

read-out delay. Naturally this depends on the middleware connecting readers together. A load balancing method has been proposed by Park et al. [28] that uses a connection pool for the middleware which enhances system flexibility and availability.

In most cases RFID is introduced in order to lower cost in the distribution chain and maintain visibility of goods during transportation or storage. This is done by using a backbone, connecting different databases used by the involved logistic companies. As an example, Yu et al. [29] propose, for mobile RFID tags, a protocol by which the reader discriminates newly arriving tags from the leaving tags. This reduces the number of readings done by the RFID-reader, and the database only has to update changes in the tag population, resulting in decreased tag read delay and higher tag read throughput.

Potdar et al. [30] propose to address the issue of non-read tags by comparing the actual weight of the tagged goods available at the reading spot with the expected when comparing to information in a database where the goods weight is stored. By doing this it is possible to know if any tags (actually any goods) were missed in the read process.

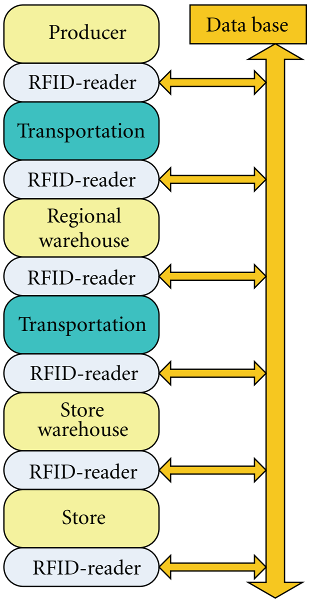


Figure 15: The database connected via the backbone, enabling continuous tracking of goods.

Table 5: The *ICW* and the coefficient values, *C*, *L*, and *E*, giving lowest energy consumption (Energy) when choosing a specific delay, 1050 tags, and the different algorithms.

			1050 Tags		
Delay (ms)	Constant (Min delay = 3825 ms)	Linear (Min delay = 4487 ms)	Linear modulus (Min delay = 3850 ms)	Exponential (Min delay = 19467 ms)	Exponential modulus (Min delay = 3947 ms)
3825	ICW = 100 ms $C = 1$ Energy = 2052 μJ				
3850	1600 ms 1 1312 μJ		ICW = 100 ms $L = 1$ Energy = 1431 μJ		
3947	3400 ms 1 477 μJ		2800 ms 1 568 μJ		ICW = 400 ms $E = 1$ Energy = 667 μJ
4487	4300 ms 4 228 μJ	ICW = 3100 ms $L = 1$ Energy = 269 μJ	4300 ms 2 228 μJ		3700 ms 2 240 μJ
5000	4900 ms 4 207 μJ	4600 ms 1 212 μJ	4900 ms 2 206 μJ		4600 ms 2 209 μJ
6000	4900 ms 42 200 μJ	4900 ms 9 199 μJ	4900 ms 25 198 μJ		4900 ms 8 198 μJ
7000	4900 ms 91 195 μJ	4900 ms 22 196 μJ	4900 ms 53 194 μJ		4900 ms 18 195 μJ
19467	4900 ms 98 195 μJ	4900 ms 100 191 μJ	4900 ms 100 191 μJ	ICW = 4900 ms $E = 37$ Energy = 191 μJ	4900 ms 100 189 μJ

This seems to be a good choice for the supermarket when customers themselves should attend to the payment of the articles at the exit.

The continued work regarding the back-off protocol will focus on how to automate the decision on how to choose the algorithm parameters to be optimized for a variety of application scenarios. The above discussion should be considered as an introduction to some of the issues for practical RFID scenarios and some of the solutions for the same.

Table 6: 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

11. Conclusions

In order to support a variety of application scenarios with different requirements on energy consumption and read-out delays we have proposed an active RFID protocol with possibility to adaptively change the back-off algorithm parameters.

For the type of active 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, based on the number of tags, selecting the correct length of the Initial Contention Window and the algorithm coefficient. For some of the scenarios the delay is of prime concern, and for some the number of tags. In all cases the energy consumption is important.

The proposed method of using a dynamic back-off scheme results in lowered average tag energy consumption (increased tag battery lifetime). A non-dynamic scheme would need to utilize worst-case parameters, yielding the highest energy consumption values in all scenarios. We show that the energy consumption per tag payload delivery can be lowered by more than 10 times by using an adaptive protocol.

The effect is that the battery lifetime of the tag will increase by as much as 50%.

To estimate the number of available tags at an RFID reader, we propose to use existing databases, for instance in the logistics chain.

Acknowledgment

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References

[1] B. Nilsson, L. Bengtsson, and B. Svensson, "An application dependent medium access protocol for active RFID using dynamic tuning of the backoff algorithm," in *Proceedings of the IEEE International Conference on RFID (RFID '09)*, pp. 72–79, April 2009.

[2] W. Dong-Liang, W. W. Y. Ng, D. S. Yeung, and H. L. Ding, "A brief survey on current rfid applications," in *Proceedings of the International Conference on Machine Learning and Cybernetics*, pp. 2330–2335, chn, July 2009.

[3] "Standards Development Process Version 1.5 EPCglobal," Board Approved February, 2009.

[4] B. Nilsson, L. Bengtsson, P.-A. Wiberg, and B. Svensson, "Protocols for active RFID—the energy consumption aspect," in *Proceedings of the IEEE 2nd Symposium on Industrial Embedded System*, pp. 41–48, Lisbon, Portugal, July 2007.

[5] ISO/IEC 18000-7:2004, Information technology—Radio frequency identification for item management—Part 7: Parameters for active air interface communications at 433 MHz, 2004.

[6] H. Cho and Y. Baek, "Design and implementation of an active RFID system platform," in *Proceedings of the International Symposium on Applications and the Internet Workshops (SAINT '06)*, pp. 80–83, January 2006.

[7] W. J. Yoon, S. H. Chung, S. J. Lee, and Y. S. Moon, "Design and implementation of an active RFID system for fast tag collection," in *Proceedings of the 7th IEEE International Conference on Computer and Information Technology (CIT '07)*, pp. 961–966, October 2007.

[8] G. Bhanage and Y. Zhang, "Relay MAC: a collision free and power efficient reading protocol for active RFID tags," in *Proceedings of the 15th International Conference on Computer Communications and Networks (ICCCN '06)*, pp. 97–102, October 2006.

[9] N. Li, X. Duan, Y. Wu, S. Hua, and B. Jiao, "An anti-collision algorithm for active RFID," in *Proceedings of the International Conference on Wireless Communications, Networking and Mobile Computing (WiCOM '06)*, September 2006.

[10] JU. P. Chen, T. H. Lin, and P. Huang, "On the potential of sensor-enhanced active RFIDs," in *Proceedings of the Emerging Information Technology Conference*, pp. 57–60, August 2005.

[11] D. Hall, D. C. Ranasinghe, B. Jamali, and P. H. Cole, "Turn-on circuits based on standard CMOS technology for active RFID labels," in *The International Society For Optical Engineering*, vol. 5837, part 2 of *Procedings of the SPIE*, pp. 310–320, 2005.

[12] S. Jain and S. R. Das, "Collision avoidance in a dense RFID network," in *Proceedings of the 1st ACM International Workshop on Wireless Network Testbeds, Experimental Evaluation and Characterization (WiNTECH '06)*, pp. 49–56, September 2006.

[13] R. Rom and M. Sidi, *Multiple Access Protocols Performance and Analysis*, Springer, New York, NY, USA, 1990.

[14] L. Leian and L. Shengli, "ALOHA-based anti-collision algorithms used in RFID system," in *Proceedings of the International Conference on Wireless Communications, Networking and Mobile Computing (WiCOM '06)*, pp. 1–4, September 2006.

[15] Z. Xie and S. Lai, "Design and implementation of an active RFID MAC protocol," in *Proceedings of the International Conference on Wireless Communications, Networking and Mobile Computing (WiCOM '07)*, pp. 2113–2116, September 2007.

[16] G. Mazurek, "Collision-resistant transmission scheme for active RFID systems," in *Proceedings of the International Conference on Computer as a Tool (EUROCON '07)*, pp. 2517–2520, September 2007.

[17] B. Nilsson, L. Bengtsson, P.-A. Wiberg, and B. Svensson, "The effect of introducing carrier sense in an active RFID protocol," Tech. Rep. IDE0766, Halmstad University, Halmstad, Sweden, February 2007.

[18] M. Taifour, F. Naït-Abdesselam, and D. Simplot-Ryl, "Neighbourhood backoff algorithm for optimizing bandwidth in single hop wireless ad-hoc networks," in *Proceedings of the International Conference on Wireless Networks, Communications and Mobile Computing*, pp. 336–341, June 2005.

[19] R. Jayaparvathy, S. Rajesh, S. Anand, and S. Srikanth, "Delay performance analysis of 802.11," in *Proceedings of the 9th Asia-Pacific Conference on Communications (APCC '03)*, vol. 1, pp. 223–226, September 2003.

[20] 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," in *Proceedings of the International Conference on Communications, Circuits and Systems (ICCCAS '04)*, vol. 1, pp. 359–363, June 2004.

[21] N. Song, B. Kwak, and L. E. Miller, "Analysis of EIED backoff algorithm for the IEEE 802.11 DCF," in *Proceedings of the IEEE 62nd Vehicular Technology Conference (VTC '05)*, vol. 4, pp. 2182–2186, September 2005.

[22] K. Joseph and D. Raychaudhuri, "Analysis of generalized retransmission backoff policies for slotted-ALOHA multiaccess channels," in *Proceedings of the IEEE International Conference on Communications (ICC '88)*, vol. 1, pp. 430–436, June 1988.

[23] P. Papadimitratos, A. Mishra, and D. Rosenburgh, "A cross-layer design approach to enhance 802.15.4," in *Proceedings of the IEEE Military Communications Conference (MILCOM '05)*, vol. 3, pp. 1719–1726, October 2005.

[24] nRF2401A, "Single Chip 2.4 GHz Transceiver Product Specifiction," Nordic Semiconductor ASA, 2007.

[25] M. Chen, W. Cai, S. Gonzalez, and V. Leung, "Balanced itinerary planning for multiple mobile agents in wireless sensor networks," in *Proceedings of the Annual International Conference on Ad Hoc Networks (ADHOCNETS '10)*, July 2010.

[26] F. Kheiri, B. Dewberry, L. L. Joiner, and D. Wu, "Capacity analysis of an ultrawideband active RFID system," in *Proceedings of the IEEE SoutheastCon*, pp. 101–105, April 2008.

[27] C. Floerkemeier, "Transmission control scheme for fast RFID object identification," in *Proceedings of the 4th Annual IEEE Conference on Pervasive Computing and Communications (PERCOMMW '06)*, pp. 462–468, March 2006.

[28] S. M. Park, J. H. Song, C. S. Kim, and J. J. Kim, "Load balancing method using connection pool in RFID middleware," in *Proceedings of the Fifth ACIS International Conference on Software Engineering Research, Management, and Applications (SERA '07)*, pp. 132–137, August 2007.

[29] J. Yu, E. Noel, and W. Tang, “A new collision resolution protocol for mobile RFID tags,” in *Proceedings of the Wireless Telecommunications Symposium (WTS ’07)*, pp. 1–10, April 2007.

[30] V. Potdar, P. Hayati, and E. Chang, “Improving RFID read rate reliability by a systematic error detection approach,” in *Proceedings of 1st Annual RFID Eurasia Conference*, September 2007.

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