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# An Active Backscatter Wake-up and Tag Identification Extraction Protocol for Low Cost and Low Power Active RFID

B. Nilsson, L. Bengtsson, B. Svensson, U. Bilstrup, and P-A. Wiberg

**Abstract**—In this paper we present a Radio Frequency Identification (RFID) protocol used to wake up and extract the ID of every tag (or a subset thereof) within reach of a reader in an active backscatter RFID system. We also study the effect on tag energy cost and read-out delay incurred when using the protocol, which is based on a frequency binary tree. Simulations show that, when using the 2.45 GHz ISM band, more than 1500 tags can be read per second. With a population of 1000 tags, the average read-out delay is 319 ms, and the expected lifetime of the RFID tags is estimated to be more than 2.5 years, even in a scenario when they are read out very often.

## I. INTRODUCTION

MOST Active RFID (A-RFID) techniques suffer from that the tag needs to be synchronized to the RFID-reader or listen for the reader in order to know when it should deliver its identification number (ID). This costs tag energy, which means lowering of the tag battery life time. Various solutions for wake-up radios have been published [1-5]. They suffer from difficulties like low receiving sensitivity resulting in short reading range, awakening due to false signals, need of cyclic synchronizing, and need for a more complex transceiver. Typically wake-up radios comes at the cost of added circuit area and the power consumption of this circuitry. In this paper, the topology used as a complete wake-up radio transceiver is one single low power, high sensitivity and small area, tunable LC-oscillator introduced by Nilsson et al. [6]. We describe a novel frequency binary tree search protocol needed to support the used topology.

This work is part of a vision to design an RFID system based on tags using a small, low cost, mixed signal, mass produced ASIC. Such a low cost active-RFID tag could compete with passive-RFID tags in terms of price (typically a few cents). Typically the tags could be used in e.g. road toll systems or when tracing goods in the logistic chain.

This paper is organized as follows; II) Short description of the hardware technology used to enable the wake-up radio. III) The binary frequency search tree protocol in detail. IV) Calculations of delay, energy consumption, and tag life time. V) Simulation results. VI) Future Work. VII) Conclusion.

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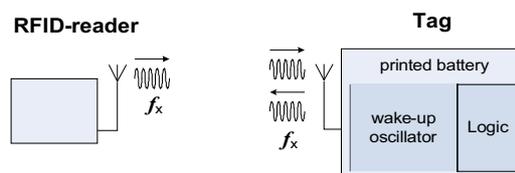


Fig 1. Active backscatter. The reader transmits a carrier wave and a tag responds on the frequency  $f_x$ . The delay until the tag responds is the signal propagation delay plus the start-up delay for the tag oscillator.

TABLE I THE SYSTEM DATA

Tag Power Consumption, Idle mode [mW]	,
Tag Power Consumption, Active mode [mW]	,
Tag Sensitivity [dBm]	-
Tag Output Power [dBm]	-
Tag Idle to Active mode [ $\mu$ s]	,
Reader transmit time [μs]	,
Tag transmit time [μs]	,
Max propagation delay [μs]	< ,
Reader Sensitivity [dBm]	-
Reader Output Power [dBm]	
System Operating Range [m]	

## II. THE WAKE-UP RADIO AND PRINCIPLE OF OPERATION

A differential LC-oscillator is used in the tags as a wake-up radio and transceiver. The oscillator is designed to consume low power by operating in the “weak inversion” region (subthreshold). The oscillator is biased near oscillation and a radio signal received by the antenna pushes the bias point (exponentially) into a region where stable oscillation is obtained. Figure 1 illustrates how the RF-signal from the reader initiates the oscillation in the tag’s wake-up radio receiver, resulting in a signal being transmitted back (backscattered) to the reader on the same frequency. The timing at 2.45 GHz, together with other data of the system, can be seen in Table 1. Idle mode in the table is when the oscillator is near oscillation, and active mode (tag is transmitting) is when it is oscillating.

## III. WAKE-UP AND TAG ID EXTRACTION

The protocol for communication between tag and reader is of the binary tree type [7-9], meaning that the ID is extracted bit by bit when traversing a binary tree detecting whether the

tag's next ID-bit is a '0' or a '1'. To extract bits in the tag ID the protocol uses **frequency signaling**. The tags in the vicinity of the reader are first awakened by a beacon signal, and the tags' IDs are extracted by using four different frequencies, where each frequency corresponds to a two-bit combination, as described in the following.

The timing for the system can be seen in Figure 2. When the reader is extracting a tag ID bit, it starts by transmitting a carrier at time  $t_0$  on frequency  $f_x$ . Tag 1, which is assumed to have no propagation delay of the received signal, starts to build up oscillation immediately, and reaches stable oscillation at  $t_2$ . The delay due to propagation of the RF signal for tag N is assumed to be 170 ns (corresponds to max distance for the system, 50 meters), after which the tag

starts to build up oscillation at  $t_1$ . At time  $t_4$  the reader stops transmitting and starts to sense the radio channel; it continues to sense until  $t_5$  and calculates an average value of the received power on the channel during this time. The reader then waits until  $t_7$  so that every tag in the vicinity of the

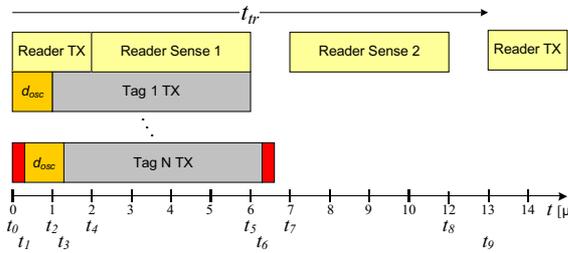


Fig 2: System timing.

reader has stopped transmitting. The reader then, during  $t_7-t_8$ , calculates an average of the received signal power when no tags are transmitting. By comparing the power levels at sense 1 and sense 2 the reader is able to distinguish between tags answering and a noisy environment. A new bit extraction cycle starts at  $t_9$ .

#### A. Frequency Coding and Allocation

The frequency spectrum allocated for the signaling is divided among five frequencies as follows.

$f_0$ : the beacon signal,  $2.4 \text{ GHz} + n_0 \text{ MHz}$ , used to wake up all tags in the reader's range.

Frequencies used in tag ID coding:

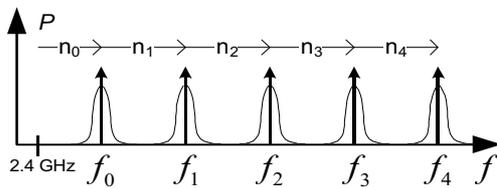


Fig 3. Frequency spectrum allocation.

$f_1$ : '00<sub>msb</sub>',  $2.4 \text{ GHz} + (n_0+n_1) \text{ MHz}$   
 $f_2$ : '10<sub>msb</sub>',  $2.4 \text{ GHz} + (n_0+n_1+n_2) \text{ MHz}$

$f_3$ : '01<sub>msb</sub>',  $2.4 \text{ GHz} + (n_0+n_1+n_2+n_3) \text{ MHz}$

$f_4$ : '11<sub>msb</sub>',  $2.4 \text{ GHz} + (n_0+n_1+n_2+n_3+n_4) \text{ MHz}$

Here,  $n_0-n_4$ , are chosen so that the frequencies are in the 2.45 GHz ISM band, shown in Figure 3.

The described frequencies are used as follows: Consider a tag with an 8-bit ID where

$$\text{Tag ID} = '10011100_{\text{msb}}$$

To address the tag with this specific ID (in order to extract its information) the following sequence would be transmitted by the reader (sequence starts with a beacon,  $f_0$ , to wake all tags in the vicinity of the reader, then specifying LSB  $\rightarrow$  MSB)

$$f_0, f_2, f_1, f_3, f_4, f_4, f_2, f_1,$$

corresponding to the *overlapping sequence* of bit-pairs '10', '00', '01', ... .

#### B. Extracting the IDs of All Tags in the Reader's Range

We now describe the process to extract the IDs of all tags within reach of the reader.

The ID extraction is initiated when the reader transmits a **beacon** (on frequency,  $f_0$ ), awakening all tags within reach. Next, the reader transmits on all four frequencies,  $f_1$  through  $f_4$ , simultaneously. A tag is initially "tuned" to the frequency corresponding to its two least significant ID bits, and the tag responds on its "tuned" frequency. The reader now knows on what frequencies there were responding tags. It randomly chooses one of these frequencies (thus selects one out of four branches in the tree to traverse, see Figure 4). The reader transmits on this frequency and tags tuned to this frequency respond. Tags not activated by the reader (because they are tuned to some of the other frequencies) are re-tuned to the beacon frequency and do not participate further in this particular ID extraction.

Recall that the reader at this point knows the two least significant bits of the tags that answered. It now uses the 2<sup>nd</sup> of these two bits to determine on which frequency to transmit next (the protocol can be viewed as a two-bit sliding window shifting one address bit to the right at a time).

If this bit is a '0' the reader transmits on frequencies that correspond to a '0' in the 1<sup>st</sup> bit,  $f_1$  and  $f_3$ . If the bit instead is a '1' it transmits on  $f_2$  and  $f_4$ . The tags, each of them now tuned to the frequency corresponding to the second and third bits of its ID, respond back to the reader if the reader transmits on their tuned frequency.

This process is iterated, traversing bit by bit, repeatedly halving the tag population until there are only two bits left, the tags' two most significant ID bits.

When reading the two last bits in the ID, done in the final reading, there are two possible bit combinations left; thus two tags can be extracted at the same time, described in the upcoming detailed example. Figure 4 shows the principle.

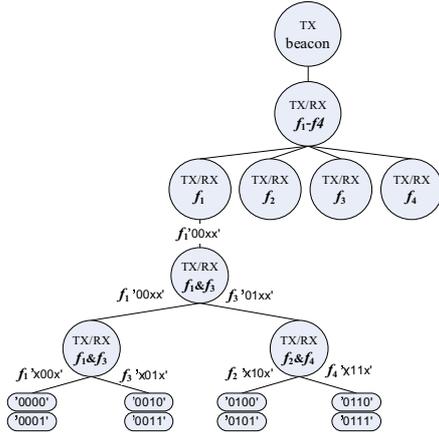


Fig 4. Structure of the frequency binary tree. The reader initiates a reading with the beacon (top level). Then it checks what frequencies  $f_1$ - $f_4$  tags are responding at (2<sup>nd</sup> level) and, in the 3<sup>rd</sup> level, it randomly chooses one of those and transmits on that frequency, in this case on  $f_1$ . In the following steps it randomly chooses a frequency to continue with until it reaches the end and has read the ID(s).

C. Identifying Unknown Tags

Figure 5 shows, in even more detail, an example of how the tag-IDs are extracted when there are four tags in reach (note that the binary coded tag-IDs, in this case 4 bits long, are shown with the most significant bit in the rightmost position, the “4<sup>th</sup> bit”). Tag-IDs are extracted in the following way:

**Step 1) Awake tags.** The reader starts the sequence by transmitting a beacon signal using  $f_0$ , awakening all tags.

**Step 2) Check what frequencies tags are tuned to.** The reader transmits simultaneously on frequencies  $f_1$ - $f_4$  and then it listens for responses from the tags on  $f_1$ - $f_4$ .

**Step 3) Choose one frequency and make tags not tuned to that frequency go to “sleep”, i.e., extract 1<sup>st</sup> bit.** In the example, step 2 indicated responses on  $f_1$  and  $f_3$ . The reader randomly chooses one of these, in this case  $f_1$ , and transmits. Tag #1, Tag #2, and Tag #4 respond. Tag #3 does not get any signal on  $f_3$  and enters sleep mode.

**Step 4) Extract 2<sup>nd</sup> bit.** Step 3 indicated that the second bit in the ID of one or more tags is a ‘0’ ( $f_1$ =‘00’<sub>msb</sub>). Then there are two possible choices for the 3<sup>rd</sup> ID bit. The reader transmits on  $f_1$  and  $f_3$ , corresponding to ‘0<sub>2nd bit</sub> 0<sub>3rd bit</sub>’ and ‘0<sub>2nd bit</sub> 1<sub>3rd bit</sub>’, respectively. Tag #1 and Tag #2 respond on  $f_1$ ; they have the 3<sup>rd</sup> bit set to a ‘0’. Tag #3 responds on  $f_3$ , because the 3<sup>rd</sup> bit is a ‘1’. If the tag ID is  $B$  bits long, Step 4 is iterated  $B-1$  times before continuing to Step 5.

**Step 5) Extract 3<sup>rd</sup> and 4<sup>th</sup> bit simultaneously.** To extract the last two bits (done in one reading), the reader transmits on frequencies  $f_3$  and  $f_4$  (3<sup>rd</sup> bit was a ‘1’). The tag response on each of the frequencies completes the full IDs of the responding tags, and this ends the read cycle. The identified tags, in this case Tag #1 and Tag #2, now enter

sleep for a pre-specified “long” time.

A new read sequence is then started by sending a beacon signal awakening tags that were not previously read. This is repeated until all tags are read.

D. Addressing a Specific Tag and Extracting Data

In some applications it is already known which tags are in the vicinity of the reader and it is of interest to selectively address them, one by one. To do this, the reader uses the frequency “trail”, which is composed of the bit combination in the tag ID, in a straightforward way. The addressing method is useful for saving tag energy, since it gives a minimal number of activations of the tags.

It is also possible for the reader to retrieve information stored on the tag (e.g. sensor data). This is done by continuing the ID read cycle, but instead of retrieving ID bits from the tag, the reader retrieves the stored data, bit by bit.

IV. CALCULATIONS OF DELAY, THROUGHPUT, AND ENERGY CONSUMPTION

There are three important parameters for an RFID system [9]. The first is the read-out delay (delay until the tag ID is read), the second is the throughput (number of tags read per time unit). Both of these parameters influence the energy consumption (energy consumed by the tag to deliver its ID) thus affecting the third parameter which is the battery life-time.

Some definitions used further on are the following:  $N$  is the number of tags in the population within reach of the reader.  $B$  is the number of bits in the tag ID.  $t_{tr}$  is the time used to extract one single ID bit from a tag, see Figure 2.

To calculate delays, equations 1-3 are used. There is a minimum delay (eq.1), for the first tag to be read, and a maximum delay (eq.3), for the last one. Eq.2 shows the average read-out delay. The ‘1’ in  $(1+B)$  is the beacon activation. Eq.4 is used to calculate the throughput (tags read per time unit).

$$Min\ delay = (1 + B) \cdot t_{tr} \tag{1}$$

$$\overline{delay} = \frac{N \cdot (1+B) \cdot t_{tr}}{2} \tag{2}$$

$$Max\ delay = N \cdot (1 + B) \cdot t_{tr} \tag{3}$$

$$Max\ throughput = \frac{1}{(1 + B) \cdot t_{tr}} \tag{4}$$

In a case with  $N=1000$ ,  $B=48$ , and  $t_{tr}=13\ \mu s$  the  $Min\ delay = 637\ \mu s$ ,  $Average\ delay = 319\ ms$ , and  $Max\ delay = 637\ ms$ . The absolute maximum throughput becomes 1570 tags per second (assuming an ideal channel with no transmission errors).

To calculate the average energy consumption for a single tag the average number of tag activations (a tag responding to a reader, trying to deliver its ID) needs to be known. If the

reader *randomly* chooses the next bit-combination to read, tags automatically get a normally distributed number of activations. That is, if the random function has a uniform distribution. If the reader instead had chosen to read tags with highest radiated signal instead of choosing randomly, then the tags closest to the reader would have had fewer activations and always less power consumption and then also longer lifetime. This might not be of relevance for scenarios where tags always move around and are not positioned at the same distance from the reader. On the other hand for those scenarios where tags are constantly positioned at the same place this is of great importance for the lifetime.

When all the  $N$  tags are awakened by a beacon, each tag oscillator is activated once, see Figure 6. The second

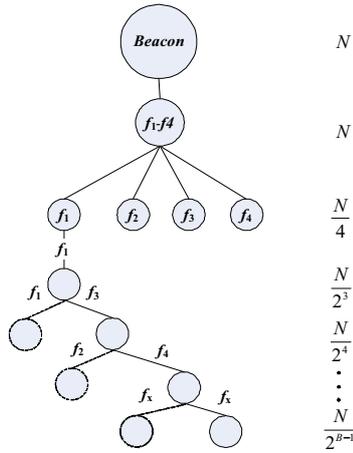


Fig 6. Calculation of the number of tag activations. The number of tags answering in each step of the ID extraction is shown to the right in the figure.

activation is when all tags receive the transmission on  $f_1-f_4$  and answer according to how their two first ID-bits are “tuned”. Next, the reader randomly chooses to continue with tags having one of ‘00’, ‘01’, ‘10’ or ‘11’ in the first two ID bits. The result is that  $\frac{3}{4}$  of the tags enter sleep (assuming a uniform distribution of tag-IDs over the address range  $1-(2^B-1)$ ), waiting for a new beacon, and only  $\frac{1}{4}$  of the tags continue the ID extraction. Further, the reader chooses one of the group’s  $f_1-f_2$  or  $f_3-f_4$  depending on the most significant bit read in the prior reading. For instance, an answer from a tag, or tags, on  $f_2$  (binary ‘10<sub>msb</sub>’) leaves the reader with one choice, to transmit on  $f_1$  and  $f_3$ . This procedure is repeated until the last two bits are reached (i.e., to bit position  $B-1$ ). At this point the last reading is done and up to two tags might be identified at the same time.

From Figure 6 we derive a mathematical expression for the sum,  $A$ , of all activations during one read sequence (between two beacons).

$$A = N + N + \frac{N}{4} + \frac{N}{2^3} + \frac{N}{2^4} \dots \frac{N}{2^{B-1}} = 2N + \sum_{k=2}^{B-1} \frac{N}{2^k} = N \left[ 2 + \sum_{k=2}^{B-1} \frac{1}{2^k} \right]$$

The sum  $\sum_{k=2}^{B-1} \frac{1}{2^k}$  approaches  $\frac{1}{2}$  when  $B$  is large, thus

resulting in the approximation  $A \approx 2.5N$ . Now it is possible to calculate the total number of activations,  $S$ , done during  $N$  beacons when reading all the tag-IDs.

$$S = \sum_{i=1}^N 2.5i$$

As  $S$  is the total number of activations done when reading all the tag-IDs, the average number of activations done for one tag to eventually deliver its ID becomes

$$\overline{\text{activations}} = \left[ \frac{2.5}{N} \sum_{i=1}^N i \right] + B,$$

where the number of bits,  $B$ , is added for the one successful time a tag is read.

## V. SIMULATIONS

The tag energy consumption calculations in Section IV are verified by simulations. Energy consumption is related to the number of activations the tag has experienced. An “activation” is when a tag responds to the reader’s transmitted  $f_0-f_4$  by transmitting on the same frequency as the reader. The tag-IDs used in the simulations are 48 bits long and uniformly distributed in the range  $1 - (2^{48} - 1)$ . The tag population is varied from 50 tags up to 10000 tags, with increments in steps of 50 tags.

### A. Simulation properties

In reality, the tag transmission will appear to the reader like Rayleigh distributed multipath fading [10]. This results in increased signal attenuation, which will decrease the system’s operating range. Inter-symbol interference (ISI) will not appear due to the selected timing in the system (Figure 2).

In the simulations the reader transmits  $f_0-f_4$  during time  $R$  and the tag responds by transmitting during the time  $T$ . The tag oscillator’s power consumption from Table 1 is used. The energy source attached to the tag is equivalent to a 3V lithium cell (CR2032, 1620 Joule, extracted from data sheet). A printed paper battery [11,12], sized 7x7 cm delivers the same amount of energy. An additional benefit of using a printed battery is the possibility of co-locating the oscillator coils and tag antenna on the battery.

### B. Simulation Results

The results from the simulations are presented as 1) read-out delay, 2) the number of activations, and 3) the tag lifetime when draining the battery.

In Figure 7, the read-out delay is shown as minimum delay, average delay and maximum delay. It can be seen in the figure that equations 1-3 in section IV corroborate the

simulated read-out delay result. With a population of 1000 tags, the average ID read-out delay is 319 ms. The number of activations for a tag is shown in Figure 8. The number of activations is used to calculate how many days a battery will last if the reader tries to read the tags every 60 seconds. If there are 50 tags available to the reader the tag life time will

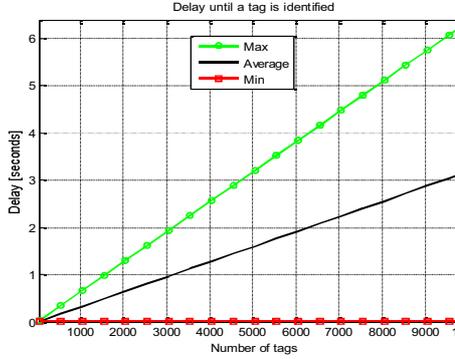


Fig 7. The ID read-out delay.

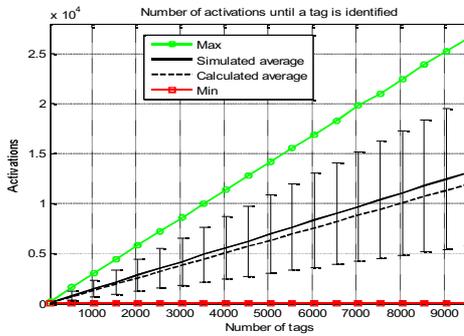


Fig 8. The number of tag oscillator activations before a tag ID is extracted (the difference between the calculated and simulated averages is due to the small tag population in relation to the tag address space). The standard deviation is added on the simulated average curve.

be 920 days, and if the population increases to 10000 tags the life time will decrease to 820 days.

C. Tag ID extraction order, LSB to MSB or MSB to LSB

We also considered the case when the IDs of a tag population are in consecutive rather than in random order. In that case we also considered reading the tags with the most significant bit first or last. This gives us three cases; 1) consecutive IDs and extract LSB first. 2) Consecutive IDs and extract MSB first. 3) IDs randomly and evenly spread in the space  $1$  to  $2^{48} - 1$  and extract in either order.

The simulation results for the three cases, each based on

can be seen that in case 2, i.e., reading consecutive tags with MSB first, the number of tag activations is much higher than in the other cases. This is because the tags only differ in their last 10 address bits, the 38 leading ones are all identical. In Figure 7 & 8 it is case 3 that is used.

D. Protocol Enhancements

Above, we have described a straightforward and non-complex protocol to extract tag IDs. Related work by Seol et al. [15] examined the possibility of enhancing the binary tree protocol used in a passive RFID system. The enhancement was done by resetting tags to the appropriate node, and not to the root node, after each consecutive read cycle, thereby reducing overall read time with 11%. The QTDSFA protocol proposed by Xin-qing et al. [14] combines dynamic frame slotted ALOHA with grouping of the tags into subgroups, in this way increasing throughput in dense tag environments. Several other studies have shown enhancements of the binary tree protocol [15-19], but to the cost of more complex algorithms and synchronization issues.

The power consumption in our protocol can be reduced, at the cost of increased read-out delay, if the tag after having received the first beacon signal makes a *beacon count delay* of  $C$  cycles (slotted channel assignment), where  $C$  equals the number of beacon cycles (figure 5, steps 1-5). Then the tag does not need to engage in the same number of identification cycles as if all tags awake at the same time and try to deliver their IDs. Slotted behavior like this is shown to be efficient [7, 9]. Selecting  $C$  is related to the required max delay and min throughput of the application. The resulting power-delay tradeoff (gained on requirements of the actual RFID application at hand) is similar to the one presented in [20].

Another way of reducing the energy consumption is to divide the search space into intervals and conduct the binary search method over each interval, as shown in [21]. This method reduces the average number of timeslots and the total number of tag responses. For the frequency binary tree protocol this method could be employed by increasing the number of frequencies the system uses.

VI. FUTURE WORK

Future work will involve investigating the use of the suggested protocol also in passive systems. A combined active/passive RFID system could be employed utilizing readers with the capability of reading both active and passive tags. Using passive tags in some scenarios gives the added

TABLE 2 COMBINING TAG ID EXTRACTION ORDER AND TAG ID SPREAD.

Combination	# Activations				# Beacons				Delay [ms]			
	min	mean	max	dev	min	mean	max	dev	min	mean	max	dev
1	49	1418	2788	770	1	500,5	1000	288,8	0,637	318,82	637,00	0,184
2	49	10302	20551	5926	1	251,2	501	144,6	0,637	160,01	319,14	0,092
3	49	1423	2946	776	1	500,5	1000	288,8	0,637	318,82	637,00	0,184

reading out 1000 tags, can be seen in Table 2. The average number of activations over 100 simulation runs is shown. It

functionality of limiting the reading range to what is typical for passive RFID.

## VII. CONCLUSIONS

Wake-up radio technology, such as the one described and used in this paper, raises a number of issues that are important also in conventional radio front ends, namely power consumption, method of synchronization, and silicon area of the mixed signal die. The low complexity and low power consumption of the backscatter radio transceiver enables low-cost tags with long reading range, two-way communication (tag – reader), and sensor logging.

In this paper we have described a frequency binary tree protocol that can be used for addressing single tags or for reading out all tags within reach from the reader.

Calculations and simulations show that the protocol enables reading 1570 tags per second and that the average delay for reading a tag ID in a population of 1000 tags is 319 ms. Using this protocol, the estimated life time for a tag powered by a low-cost 7x7 square centimeter printed battery, is almost three years, in a scenario when the tag's ID is read out once every 60 seconds at a population of 50 tags.

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