A Snoozing Frequency Binary Tree Protocol

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Abstract **– In this paper we describe and evaluate an enhanced version of an active RFID wake-up and tag ID extraction radio communication protocol. The enhanced protocol further reduces the transponders' power consumption (prolonging their battery lifetime). The protocol uses a frequency binary tree method for extracting the identification number of each transponder. This protocol is enhanced by extending it with a framed slotted medium access control method which decreases the number of activations of each transponder during tag ID extractions. Using this medium access method, the average number of transponder activations is decreased with a factor of 2.5 compared to the original protocol. The resulting increase in ID read-out delay is 0.9%, on average.**

I. Introduction

Transponders for Active RFID technology can be divided into at least two groups, namely, transponders based on cyclic awakening, and transponders using a wake-up radio. In this paper we focus on wake-up radio based transponders (tags) with the ability to "come alive" when they are in range of an RFID Interrogator (RFID-reader), without having to listen periodically for a reader to know when to deliver their identification number.

Thanks to the CMOS evolution, leading to decreasing transistor size, chip area and power consumption, wake-up radio circuits have been established and continued to evolve [1-5]. In this paper the tag wake-up architecture is based on a single LC-oscillator, as described in [6]. 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 into a region where stable oscillation is obtained. The RF-signal from the RFID-reader initiates the oscillation in the tag's wake-up radio transceiver, resulting in a signal being transmitted back (backscattered) to the reader on the same frequency.

We have previously, in [7], described a novel active RFID protocol to support wake-up radio architecture for low power active RFID. In this paper we describe and evaluate the same frequency binary tree protocol enhanced with a medium access control method (MAC) to reduce power consumption even more. The enhancement is done by using a framed and slotted MAC method [8] including a simple back-off strategy to minimize the number of tag activations during read-out of the tag IDs.

II. The Original Protocol

The method used to extract a tag identification (ID) number is of the binary tree type [8-10], 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'. Bits are extracted by using ***frequency signaling***. The tags in the vicinity of the reader are first awakened by a broadcasted beacon signal, and the tags' IDs are extracted by using four different frequencies, where each frequency corresponds to a two-bit combination, described as follows.

The timing for the system can be seen in Figure 1. When the reader is extracting a tag ID bit, it starts by transmitting a carrier at time t_0. 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 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 received energy for 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.

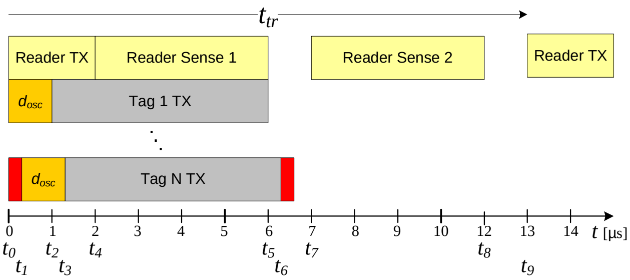

Figure 1: System timing.

2.1 Frequency Coding and Allocation

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

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

Frequencies used in tag ID coding:

$\boldsymbol{f_1}$: '00_{msb}', 2.4 GHz+ (n_0+n_1) MHz
$\boldsymbol{f_2}$: '10_{msb}', 2.4 GHz+ ($n_0+n_1+n_2$) MHz
$\boldsymbol{f_3}$: '01_{msb}', 2.4 GHz+ ($n_0+n_1+n_2+n_3$) MHz
$\boldsymbol{f_4}$: '11_{msb}', 2.4 GHz+ ($n_0+n_1+n_2+n_3+n_4$) MHz

Here, n_0-n_4 are chosen so that the frequencies are in the 2.45 GHz ISM band, shown in Figure 2.

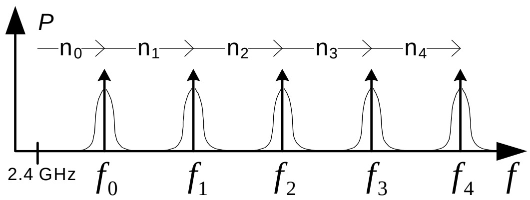

Figure 2. Frequency spectrum allocation.

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

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

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, $\boldsymbol{f_0}$, to wake all tags in the vicinity of the reader, then specifying LSB → 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’, … .

2.2 Extracting the Tag IDs in Range of the Reader

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, $\boldsymbol{f_0}$), awakening all tags within reach. Next, the reader transmits on all four frequencies, $\boldsymbol{f_1}$ through $\boldsymbol{f_4}$, 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 3). 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 2nd 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 1st bit, $\boldsymbol{f_1}$ and $\boldsymbol{f_3}$. If the bit instead is a ‘1’ it transmits on $\boldsymbol{f_2}$ and $\boldsymbol{f_4}$. 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, which is done in the final reading, there are two possible bit combinations left; thus two tags can be extracted at the same time, shown in Figure 3.

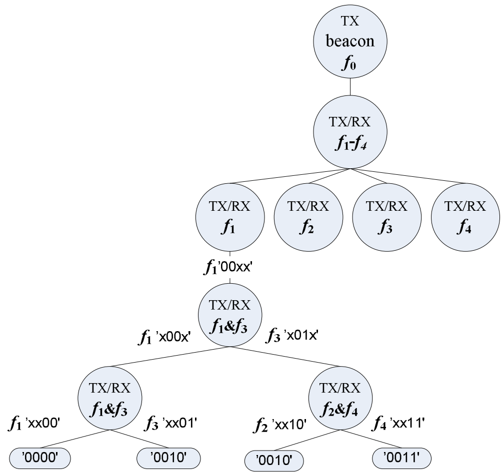

FIGURE 3. STRUCTURE OF THE FREQUENCY BINARY TREE. THE READER INITIATES A READING WITH THE BEACON (TOP LEVEL). THEN IT CHECKS WHAT FREQUENCIES F1-F4 TAGS ARE RESPONDING AT (2ND LEVEL) AND, IN THE 3RD LEVEL, IT RANDOMLY CHOOSES ONE OF THOSE AND TRANSMITS ON THAT FREQUENCY, IN THIS CASE ON F1. IN THE FOLLOWING STEPS IT RANDOMLY CHOOSES A FREQUENCY TO CONTINUE WITH UNTIL IT REACHES THE END AND HAS READ THE ID(S).

III. THE ENHANCED PROTOCOL

The enhanced protocol uses a framed and slotted MAC method [8] and works as follows, see Figure 4. When the tag is awakened by the first beacon signal, transmitted by the RFID reader, it randomly chooses a slot in the pre-defined frame and sets the beacon counter to that random number. When the tag is subsequently awakened by beacon signals it counts down the beacon counter (snoozes until next beacon). When the beacon counter reaches zero, the tag tries to deliver its ID by using the binary tree method previously described for the original protocol. This procedure is continued until the tag successfully has delivered its tag ID, then it enters deep-sleep mode and does not encounter in further ID extraction for a pre-determined time.

IV. CALCULATIONS OF TAG ACTIVATIONS

To optimize the tag battery lifetime the number of tag activations should be minimized. Here we show how to calculate the average number of tag activations when using the enhanced protocol.

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. F is the number of slots in the frame.

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 of choosing randomly, had chosen to read tags with highest radiated signal, 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 3. The second activation is when all tags receive the transmission on $\boldsymbol{f_1}$-$\boldsymbol{f_4}$ and answer according

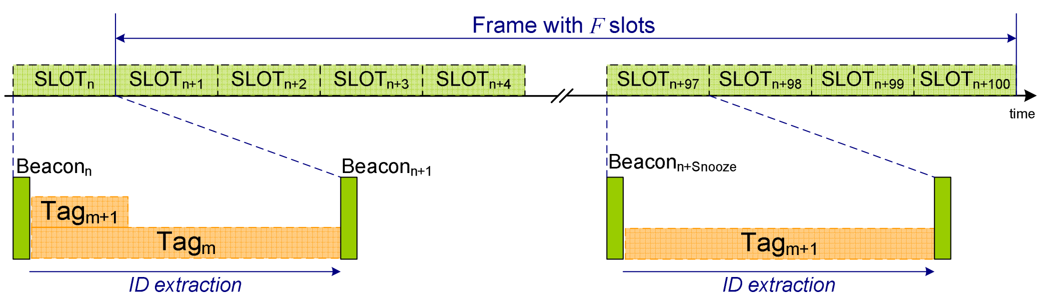

FIGURE 4. AFTER Beacon$_n$, Tag$_{m+1}$ CONTENDS WITH Tag$_m$ TO DELIVER ITS ID. Tag$_{m+1}$ IS NOT SELECTED BY THE READER AND RANDOMLY CHOOSES A NEW SLOT IN A NEW FRAME WITH F SLOTS (F=100) TO WAKE UP IN. IT SNOOZES UNTIL THE CHOSEN SLOT ARRIVES, AND ONCE AGAIN IT TRIES TO DELIVER ITS ID AND SUCCEEDS.

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 ¾ of the tags enter sleep (assuming a uniform distribution of tag-IDs over the address range), waiting for a new beacon, and only ¼ of the tags continue the ID extraction. Further, the reader chooses one of the groups 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_{msb}') leaves the reader with one choice, to transmit on f_1 or 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 this we derive a mathematical expression for the number, *A*, of activations during one read sequence

$$A = N + N + \frac{N}{4} + \frac{N}{2^3} + \frac{N}{2^4} \cdots \frac{N}{2^{B-1}} =$$

$$= 2N + \sum_{k=2}^{B-1} \tfrac{N}{2^k} = N\left[2 + \sum_{k=2}^{B-1} \tfrac{1}{2^k}\right].$$

The sum $\sum_{k=2}^{B-1} \frac{1}{2^k}$ approaches ½ when *B* is large, thus resulting in the approximation $A \approx 2.5N$. But, due to the framed slotted MAC method used, the number of tags that are awake becomes *N*/*F*, where *F* is the number of slots in the frame. Now it is possible to calculate the total number of activations, *S*, done during *N* beacons when reading all the tag-IDs.

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

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

$$\overline{activations} = \left[\frac{2.5}{NF}\sum_{i=1}^{N} i\right] + \frac{N}{2} + B,$$

where the term *N*/2 is the average number of beacon activations for each tag and the number of bits, *B*, is added for the one successful time a tag is read.

V. Simulation Results

Simulation results of the frequency binary tree (FBT) and the enhanced frequency binary tree (EFBT) protocols are shown in Figures 5 and 6. The frame used in the simulation contains 100 slots. When using the enhanced protocol the average read-out delay of the tag IDs with a population of 1000 tags is only increased by 0.9% while the maximum delay is increased by 17%. The number of tag activations for the EFBT protocol is decreased by 2.5 times compared to the original protocol. Thus the new protocol will increase the lifetime of the tag battery without deteriorating the tag ID read-out delay significantly.

VI. Future Work

6.1 Frame Length Selection

Further studies will be conducted on this protocol on how to optimize the selection of the frame length[1] according to the tag population and the specific application scenario at hand. Earlier work [11, 12] shows good results when predicting the accurate frame length according to the tag population.

6.2 Beacon Commands

The EFBT protocol has one disadvantage compared to only using the FBT method, and that is the ability to address one single tag when using the "frequency trail" described earlier. One solution to manage the single tag selection could be to vary the length of the beacon signal depending on the intention of the reader. Different distinct lengths of the beacon signal could add the possibility of giving the tags different commands.

VII. Conclusions

In this paper we have proposed an enhanced protocol to extract the identification number from an active RFID transponder. A frequency binary tree method is used to extract the transponder identification number, and a framed and slotted medium access control (MAC) method is used to access the radio channel. When combining the MAC method with the frequency binary tree method the result is a reduced number of transponder activations, which in turn decreases the transponder power consumption and thereby extends the transponder battery lifetime. Calculations and simulations show that the number of tag activations is significantly lowered. For a population of 1000 tags the average number of tag activations is decreased with a factor of 2.5, while the resulting increase in tag ID read-out delay is, on average, only 0.9% and maximum 17%.

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[1] When optimizing the number of slots, *F*, in the frame its possible to minimize the number of tag activations and thereby decreasing the tag energy consumption even further.

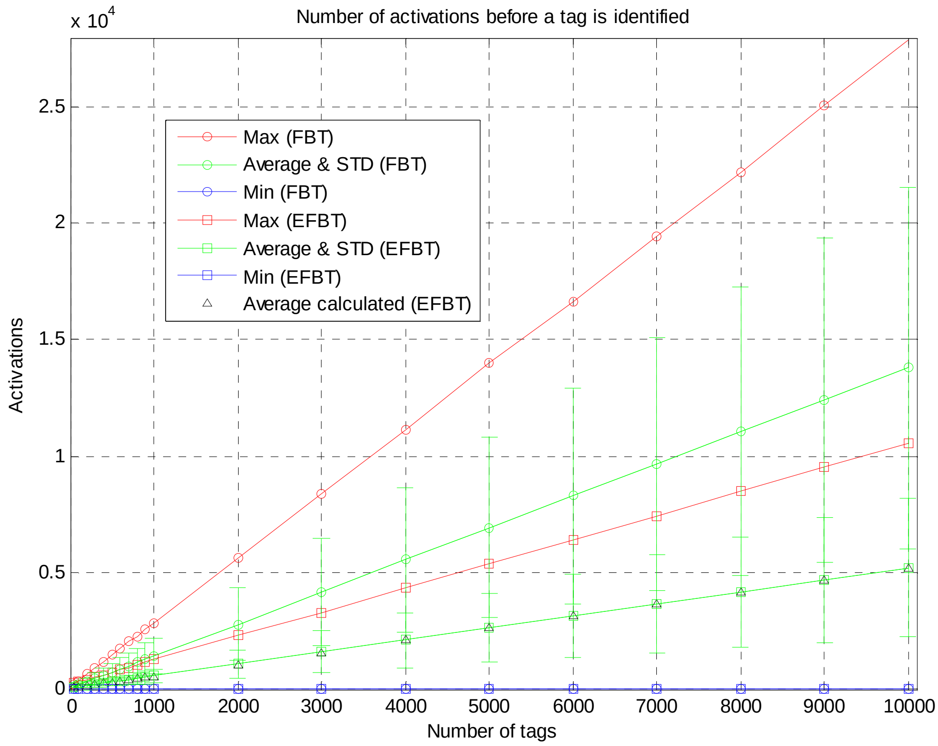

FIGURE 5. WHEN USING THE ENHANCED PROTOCOL (EFBT) THE AVERAGE NUMBER OF ACTIVATIONS WITH A POPULATION OF 1000 TAGS IS DECREASED BY 2.5 TIMES. THE MAXIMUM NUMBER OF ACTIVATIONS IS DECREASED BY 2.2 TIMES. THE CALCULATED AVERAGE FOR THE ENHANCED PROTOCOL COINCIDES WITH THE SIMULATED AVERAGE.

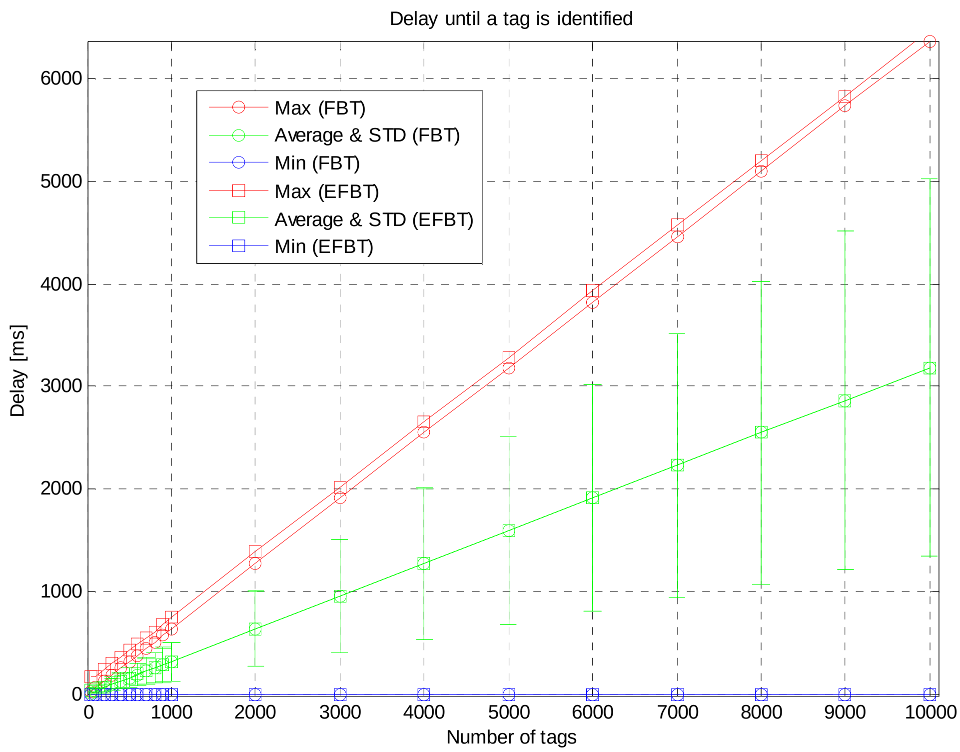

FIGURE 6. THE DELAY OF THE TWO PROTOCOLS. FOR EXAMPLE, WHEN THERE ARE 1000 TAGS AVAILABLE TO THE READER, THE ENHANCED PROTOCOL HAS AN INCREASED MAX DELAY OF 17 %, BUT THE AVERAGE DELAY WITH THE SAME NUMBER OF TAGS IS ONLY INCREASED BY 0.9 %.