To read transmitter-only RFID tags with confidence

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Abstract: Radio frequency identification (RFID) enables everyday objects to be identified, tracked, and recorded. Because of expense, size, and lifetime requirements, some simple active RFID tags are designed with only a transmitter. The transmitter-only tags are unaware of each other and simply blink ID packets periodically. The question is how we can read the tags with enough confidence. This paper models the access protocol as pure ALOHA and develops a mathematical analysis to identify tag blinks within the interrogation zone without prior knowledge of the number of tags. We estimate the tag set based on the free channel in the observation window. Some simulation results and test experiments with Spider tags from RFCODE are presented.

Keywords: RFID, multiple accesses, transmitter-only tag

I. INTRODUCTION

The radio frequency identification (RFID) enables ubiquitous tagging by attaching RFID tags with individual IDs to everyday objects [1]. This is an advantage in term of tracking objects, monitoring security and event status, and recording environment conditions from a distance without being in line-of-sight.

An RFID system consists of a reader and a number of tags [1]. The tags are small size, low cost and low power devices. The RFID tags can be either active or passive [1]. The active ones are continually powered by battery, while the passive ones have no internal power and reflect energy from the reader for communication. Consequently, the active tags can be read from a greater distance than the passive tags.

The RFID tags have restricted cost, sizes and lifetime requirements [1, 2]. The highest price of active tags must be below one US dollar for significant market penetration. The lifetime of active tags is over when the battery is exhausted since it is uneconomical to replace or recharge the battery because of large number of small and cheap nodes. As a result, the RFID tags have to work in a resource-scarce environment, where power consumption, computational capacity, memory storage and even gate counts are highly limited. Furthermore, limited available bandwidth and simplicity of tags means that all tags must share the same broadcast channel. This leads to mutual interference when there is more than one tag within the interrogation zone of a reader, which is known as packet *collision*. Many consecutive collisions of the same frame can make the reader think a tag is not in the interrogation zone. This event is known as *false alarm*.

Even though radio communication has high energy demand, reception of short range radio devices, e.g. active tags, uses almost as much energy as uplink transmission. Tags can enter a sleep state in which the radio reception is disabled [3]. Some active tags even are designed to have only a transmitter [4, 5]. The Spider tag from RFCODE is a transmitter-only tag with typical lifetime of five years. This kind of tag is particularly suitable for use in location tracking in large areas, e.g. theme parks, airports and warehouses. The tags are unaware of each other, and broadcast their ID packets, called *blinks*, periodically to indicate their existence. There is a pause called *thinking time* between two consecutive blinks. A group of children equipped with this kind of tag, for instance, can be tracked inside their kindergarten. The system boundary is the limit from where the reader cannot receive signals from the tags. When a child crosses a no-go border, the reader activates an acoustic alarm to indicate what happened. Though this procedure is simple, we would like to raise a question. How does the system know what really happened? Was it a *false alarm* due to consecutive *collisions* or was it a child crossing the border? A boy could be kidnapped in the kindergarten. Since a kidnapper is aware of this location tracking system, he may simply put the boy's tag into a Faraday cage to hide the blinks. The system must report the blink missing alarm as soon as possible, as well as not generate too many false alarms. The confidence in the alarm must be guaranteed. As there is no receiver in the tag, we cannot perform point-to-point communication to confirm what happened.

The access of these kinds of systems can be modelled as the pure ALOHA system [6]. The success of a transmission depends on the thinking time, the size of blink and the number of tags inside the interrogation zone. We must assume that the number of tags is not known in advance if we consider that the monitored area might be larger than the interrogation zone of one reader. The tags may freely cross a reader's border and enter the radio range of another reader. Originating in the communication field, most the researches on ALOHA focused on maximizing the system throughput. Various extensions of pure ALOHA were developed, including slotted ALOHA, reservation ALOHA and p-persistent ALOHA [6]. In the RFID field, the important factors are the low access delay and the low energy consumption [2]. The allowable identification delay is an application dependent constraint. Vogt used the Markov process to analyze the framed ALOHA accessing of passive tag [7]. Zhen *et al.* proposed a combinatory mode to simplify framed ALOHA analysis and gave new frame length update algorithms for both active and passive tags [8]. All these access protocols deal with a tag with one receiver and the transmission of tags can be totally or partially controlled. Assuming that the tag number is known, Hernandez *et al* developed a recursive model to read spontaneous tag transmissions to a certain confidence level [5].

In this paper, we mathematically analyze to the identification of transmitter-only tags within the interrogation zone without knowing the number of tags. The next section describes a combinatory model of pure ALOHA access of RFID system, and tag set estimation based on free channel. Simulations and test experiments on Spider tags are given in Section 3. Finally, section 4 concludes the work.

II. ALOHA ACCESS OF RFID SYSTEM

In this section, we assume that all transmitter-only tags blink with the same configuration and are independent of each other. The tags are more or less static during the time that the reader makes any decision [7]. We also assume that the channel is free of noise. And, any blink collision results in an error read.

A. Blink collision analysis

Consider a RFID system with a reader and N transmitter-only active tags. The average blink interval is β, and the blink size is T_0. The interval between two neighbouring blinks from a tag can be defined by an exponential random variable t,

$$p(t) = \frac{1}{\beta} e^{-t/\beta} . \quad (1)$$

As in pure ALOHA access, we can define a collision window of size $2T_0$, which is plot in Fig. 1 [6]. In a blink cycle, the probability of none of N-1 blinks colliding with the ongoing blink B1 is given by

$$p_c(N) = e^{-2T_0(N-1)/\beta} . \quad (2)$$

The maximum throughput can be obtained by letting

$$\frac{d(Np_c(N))}{dN} = 0 , \quad (3)$$

where $\frac{d(.)}{dN}$ denotes the derivative. Now, consider M consecutive blinks from a tag. The probability that none of them will be correctly received by the reader is

$$p_c^M(N) = \prod^{M}(1 - p_c(N)) \cdot \quad (4)$$

We cannot statistically expect to identify all tags with complete certainty. The probability of missing M consecutive blinks from a tag is the confidence in an *alarm*. In order to trigger the alarm event with a confidence , M must be

$$M \geq \frac{\log(1-\alpha)}{\log(1-p_c(N))} . \quad (5)$$

The minimum blink read time, R_{min}, can be achieved with an optimum blink interval, β_{min},

$$R_{min} = \min(M/\beta) . \quad (6)$$

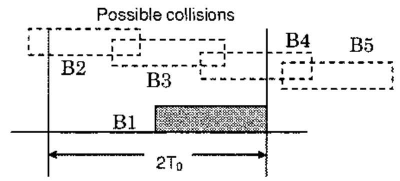

Fig. 1 Collision window of ALOHA access

In Fig. 2 we calculate the blink cycle and blink read time to a confidence =*0.99*. Both the blink read time and the blink interval are normalized by T_0. The tag set is from 50 to 500 with a step of 50. As expected, given a tag set, with increments in the blink interval, the blink read time reduces sharply to its minimum, R_{min}, and then increases slowly. Figure 2(b) shows that two blink intervals can satisfy the same blink read time requirement. The shorter one is located in the unstable area of pure ALOHA, while the longer one is in the stable area and gives fewer blink cycles [6]. Fewer blink cycle means less battery consumption since the tags blink once in a cycle. The minimum blink read times and the associated expected blinks are labelled as diamond shapes in Fig. 2(a) and (b), which are redrawn in Fig. 2(c) and (d). We can see that the optimum blink interval can be linearly fit as $\beta_{min}=2.8N$. To reach =*0.99* using β_{min}, the necessary blinks are less than 7. Thus, we can obtain the minimum blink read times of $R_{min}=18.76N$. Comparing Fig. 2(a) with (b), we can see that the downward rate of tag blinks is larger than the upward rate of blink read time when R_{min} is achieved. This means that more battery power can be saved at a little expense to the blink read time. For example, given $N=200$, when we increasing the blink read time by 10% from its minimum; the tag blinks falls from 6.65 to 3.98. That is equivalent to a 40.2% reduction in battery consumption.

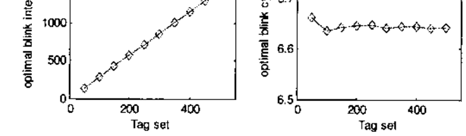

Fig. 2 Blink reading of transmitter-only active tags to =*0.99*: (a) blink cycles, (b) blink read time, (c) optimum blink intervals, and (d) optimum blink cycles

B. Tag set estimation

It is well known that, with more nodes contending a single channel, the channel become busier and there is less free time. In this section, we estimate the tag set based on the free channel size.

For an ongoing blink, if there is no other blinks occurring within T_0 after it, the channel becomes free. In Fig. 1, the channel after blink B1 is free as long as there is no blink B4. It does not matter whether blink B3 occurs or not. The probability of this happening can be given by

$$P(t > T_0) = \int_{T_0}^{\infty} p(t)dt = e^{-T_0/\beta}. \tag{7}$$

Therefore, the expect size of the free channel has the conditional probability,

$$\begin{aligned} P_f &= \int_{T_0}^{\infty} tp(t)dt \Big/ \int_{T_0}^{\infty} p(t)dt - T_0 \\ &= e^{-T_0/\beta}(T_0 + \beta) / e^{-T_0/\beta} - T_0 = \beta \end{aligned} \tag{8}$$

For a tag set N, the total number of blinks which are not followed by other blinks within T_0 is

$$N'(N) = Ne^{-T_0(N-1)/\beta}. \tag{9}$$

Therefore, the total free channel can be given by

$$C_f = mean(N'(N) * p_f). \tag{10}$$

Figure 3 depicts the relationship between the normalized free channel and the tag set. The five example blink intervals are from one to five seconds, and the blink is 5.36 ms (see simulations in next section). Given a blink interval, the free channel falls monotonously with the size of tag set. Therefore, we can estimate the tag set from the measured free channel. The marked symbols denote the free channel size obtained from simulation in next section. We use an average window of three to remove the randomness and to guarantee estimation accuracy. We can see good agreement between the analysis and the simulation.

When we read transmitter-only RFID tags, the first several blink are used to estimate the number of tag within the interrogation zone. Then we can obtain the necessary number of blinks to the confidence as per Eq. 5. We need several additional blinks to combat the random read jitter.

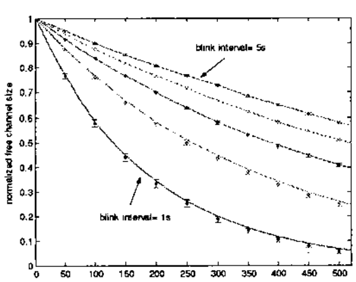

Fig. 3 Free channel size *vs* tag set

III. SIMULATIONS AND EXPERIMENTS

A. Simulations

We simulated the INCITS 371.2 which defined a real-time location system operating at 433 MHz [9]. Figure 4 describes the defined blink and sub-blink structures. Each blink contains one to four sub-blinks which are identical to provide time diversity. The blink occurs at the beginning of the blink interval, which is randomized by ±480 ms to avoid repeatedly colliding with blinks from other tags. The minimum value of the configurable blink interval is 1 s. The sub-blink is separated by a constant interval which is randomized with a start value of 300±48 ms from the beginning of previous sub-blinks. The sub-blink data packet is defined by the ISO/IEC 18000-7 draft, which consists of a preamble, data bytes and final logic low period [5]. Data bytes are sent in Manchester code formation, and are modulated by Frequency Shift Keying (FSK) in physical (PHY) layer. A blink which consist of 14 bytes lasts approximate T_0=5.36ms. The simulated blink intervals were from 1 s to 10 s with a step of 0.2 s. The number of sub-blink is one so as to compare the simulation and the analysis since we must perform all sub-blinks in a blink cycle. The confidence was set to 0.99. The tag sets are from 50 to 500 with a step of 50. Each simulation was run 300 times.

Figure 5(a) plots the good blink reading with different blink intervals. The tag sets are from 100 to 500 with a step of 100. To compare the simulations with the analysis, the blink intervals and the blink read time shown in Fig. 5(b) and (c) are normalized by T_0. We can see good agreement between them. The maximum difference in the optimum blink interval is less than 10%. Figure 5(d) shows the associated blink cycles when using the optimum blink intervals.

Because of the randomness of ALOHA access, we must average free channel measurement in several blink cycles. Figure 6 shows the tag set estimation using different observation windows which is 1, 2, 4, 7, and 10 according to tag sets and blink intervals. The tag set estimation errors are normalized, and the dashed lines denote zero errors. As expected, a large average window reduces both the tag set estimation error and its standard deviation. A larger error occurs in the case of a small tag set and a short blink interval. As shown in Fig. 6(a), given a blink interval, the tag set estimation error does not change much as per tag set, while Fig. 6(b) shows that a larger blink interval giving better tag set estimation. To balance blink read time and estimation accuracy, we use an observation window with the size of three. Figure 3 plots the simulated free channel measurement. The corresponding maximum relative tag set estimation error is 6.2% with a standard deviation of 5.9%.

We then simulated a constant blink interval of 3 s. There are two additional blink cycles which lasts 6 s. Figure 7 shows the total blink read time and the final confidence level. The maximum discrepancy between the simulations and the analysis on blink read time is 7.43 s. All the finial confidence levels are above 0.99.

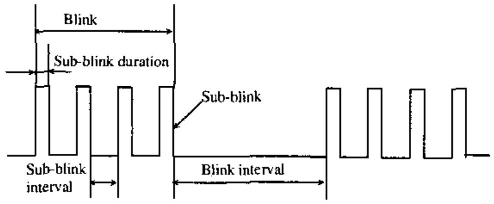

Fig. 4 Blink and sub-blink structures of INCITS 371.2

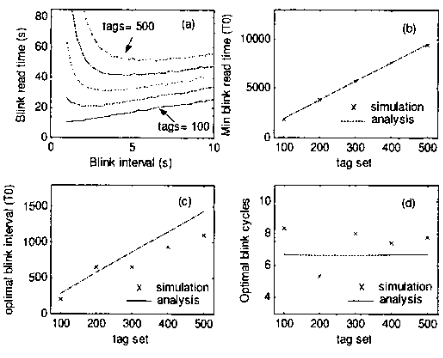

Fig. 5 Simulations on transmitter-only tag blink reading ($=0.99$): (a) blink read time, (b) minimum blink read time, c) optimum blink intervals, and (d) optimum blinks.

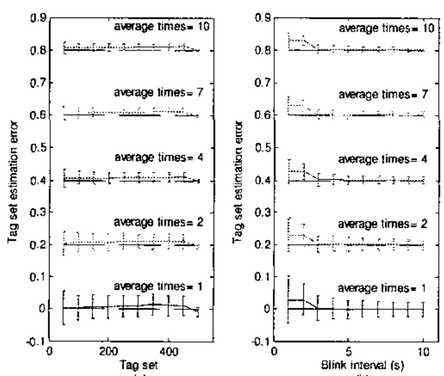

Fig. 6 Relative mean error and its standard deviation of tag set estimation as per: (a) tag set, and (b) blink interval.

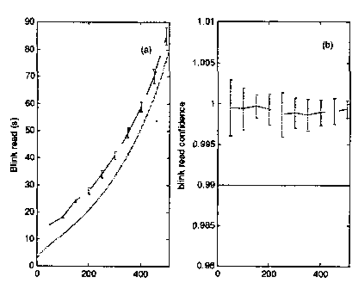

Fig. 7 Blink reading of transmitter-only active tags: (a) blink read time, and (b) final read confidence.

B. Experiments

We conducted an experiment using transmitter-only RFCODE Spider tags whose read range is approximately 100m in the indoor environment [4]. The tags are attached to persons or objects in our laboratory office, which is about 30m*100m in size. Some objects could move or be moved randomly, e.g. people and vacuum cleaners. We therefore could not control the movement of the tags during experiment. The Spider tags emit a continual blink signal with average interval of 7 s and a 1 s dither. The blink is composed of 23 pulses of which there are 7 command pulses. The Spider tag ID is a 7-byte ASCII string, which is transmitted twice in a blink. Each pulse lasts 122 s and the total blink lasts 200 ms. Blinks from different tags may interleave each other. The total blink is coded by pulse position and is then modulated by On-Off Keying (OOK) over wireless channel at 300 MHz. (Since the data book of Spider tag from RFCODE is not available, all the data is provided from an oscilloscope.)

The free channel measurement is not supported by the Spider reader. The wrong blinks are simply discarded. We cannot verify this measurement in the experiment.

In total we observed nearly 700 tags. We changed the number of tags by adjusting the sensitivity of the Spider reader [4]. The signal below the threshold is considered as noise. There are eight attenuation levels in the incoming radio signal. All blink read tests lasted more than 20 minutes. The data collected in the first 10 minutes was discarded since the reader only report a tag ID after read it four times. We segmented the test data into sessions of 45 s.

Figure 8(a) shows the average number of new tag IDs along with the blink reading in a session, which is the percentage of the accumulated good read tag IDs in the total tag set. This can be considered as the blink read confidence. Not surprisingly, the confidence suffers with increasing tag number. We can see that, in the first blink cycle, the test good blink confidence is larger than the analysis confidence. With an increase in the tag set, the confidence difference increases. The analysis confidence converges to 1 after several blink cycles, while it becomes harder to find new tag IDs in the real test. This could be attributed to the so-called "capture effect", which enables the receiver to recover the strongest signal or the earliest arrival signal out of multiple packets [10]. Because the tags were distributed throughout the complex indoor environment (walls, desks, chairs, and cabinet), blinks from some tags are much weaker. As a result, they have less chance of be received correctly than the strong blinks. This breaks our analysis assumption. Figure 8(b) shows the number of good blinks of all tags in a read experiment. The tags are sequenced in the order they are first identified. Tag IDs read after the first blink cycle are indicated by a red dashed line. The good blinks from those tags are fewer than those from the tags read in the first blink cycle. Fewer good blinks mean fewer chances to be read correctly. Another reason is the background noise. The office is pretty noisy because it is full of machines. The weak blinks are easy to be corrupted by the noise. The third factor contributing to the discrepancy is that we assume the blink interval has an exponential distribution in simulation. The Spider tags blink in a constant interval with only a little dither.

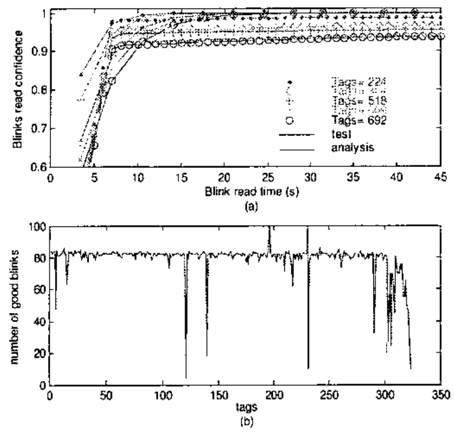

Fig. 8 (a) Spider tags reading, and (b) number of good blinks

IV. DISCUSSION AND CONCLUSION

Most of the researches on pure ALOHA aim to maximize the system throughput [6]. The greatest throughput of pure ALOHA system is achieved when the normalized offered load is 0.5 [6]. As shown in Fig. 2, the greatest throughput cannot achieve the least blink read time with a certain confidence. The optimum blink intervals to confidence 0.99 are larger than the blink interval which maximized the system throughput. Equation 5 shows the trade-off among alarm delay, confidence, and energy consumption. Equation 5 also limits the boundary performance with a given tag set.

The free channel measurement can be implemented in PHY or media access control (MAC) layer at the reader side. When implemented in the PHY layer, the reader can perform a simple receive signal strength indicator (RSSI) measurement. During the observation window, the reader just sums all the time segments when the RSSI is above a threshold. However, this method suffers from the very short burst noise and not all modulations are supported, e.g. PPM and OOK, in which there are many space. Also, it is hard to support different modulation scheme in a tag. Alternatively, free channel measurement implemented in MAC layer can be more flexible and is independent of the modulation schemes. The cost is the burden at the MAC layer. The PHY layer must report every packet demodulated to the MAC layer, no matter it is correct or wrong. The MAC adds up all bits received and normalizes them as channel traffic. The MAC then discards all the wrong packets before forwarding them to upper layer.

Since all the transmitter-only tags blink in every cycle, we cannot tell the status of a tag with full confidence [7, 8]. As shown in the Spider tag experiment, the tag reading may suffer from the capture effect. The weak blinks have less chance of being identified than the strong blinks do. One solution is to add RSSI as another fact to be considered in alarm reporting. For a weak blink, we must wait for more blink cycles for the defined confidence. However, the cost is long alarm latency. Randomizing the tags' transmission power mitigates the affect of capture effect upon a tag by averaging the alarm latency of all tags. The third way is to increase the reader's attenuation level. The capture effect is mitigated with the reduction in radio range of the reader and the number of tags clustering around the reader. By putting more readers in the field, we can benefit from space diversity and combining techniques as well. A blink may be detected with different strengths by readers at different positions. A 'no' from a reader can be negated by a 'yes' from another one. Therefore, we can guarantee the confidence in an *alarm*.

The benefit of pure ALOHA access is its simplicity. The reader and tag have only receiver and transmitter hardware, respectively. There is no detection and recovery mechanism. In addition, its implementation in chip is simple. As a result, the total system can be very cheap.

In conclusion, we investigated multiple read of transmitter-only RFID tags in this paper. Our problem is to report an *alarm* in the least time with the defined confidence when the number of tags is not known in advance. We presented a mathematical model to describe the blink reading process and a tag set estimation based on the free channel. The simulations agreed with the analysis, and the tag blinks were read above the defined confidence. We also conducted test experiments with Spider tag from RFCODE.

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