# Expanding Horizon and Capture Effect in RFID Systems
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***Abstract*— RFID has been the subject of much research recently, which yielded very efficient singulation algorithms, such as Tree Walking Algorithms [4], [5] or framed slotted Aloha [6]. However, there is still room for improvement in the case of multiple readers, and also in the power efficiency of singulation algorithms. This paper addresses two schemes that might improve energy consumption and singulation time in RFID systems. First, we consider expanding horizon, a form of power control at the reader introduced in [3], and see how it impacts the energy consumption and singulation time in the case of a single reader. Then, we study the importance of the capture effect in the multiple readers case, and present an alternative to TDMA scheme, which greatly reduces the singulation time in our simulations.**

## I. Expanding Horizon

### *A. Background*

Some work has been done in order to reduce the energy consumption of singulation algorithms for RFID [1], [2]. The main approach was to design power-efficient singulation protocols. However the savings achieved are usually pretty small. Our approach is different: instead of modifying the singulation protocols, we use a scheme - expanding horizon - that is independant of the underlying protocol, to achieve power control at the reader. First, we define what we call expanding horizon, and analyse its impact on the time required to read a population of tags, and the energy consumed at the reader. We establish the optimal expanding scheme, then compute the theoretical time complexities and energy consumption one can achieve using it, and conclude by giving an adaptive algorithm to approximate this scheme.

### *B. Definitions and notations*

We call tags singulation the process of identifying a set of tags. We call expanding horizon the scheme where a reader gradually increases its power, and thus its reading range. The transmit powers are $P_k$, and correspond to reading ranges $R_k$. We call phase $k$ the process of identifying tags at power $P_k$. At phase $k$, the reader reads tags within distance $R_{k-1}$ and $R_k$. Let $T(u)$ denote the expected time for identifying $u$ tags. We assume that $T$ is a convex function[1]. Let $N$ be the total number of tags, $N_k$ the number of tags within $R_{k-1}$ and $R_k$, $T_k$ the expected time required to identify these tags, and $p$ the number of transmit powers.

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[1]Which is the case for all the known algorithms

### *C. Singulation Time*

In this section, we determine the scheme minimizing the singulation time.

### *D. Optimal $N_k$*

Here, we first determine, given a number $p$ of power levels, the optimal $R_k$.

$$T = \sum_{k=1}^{p} T_k = \sum_{k=1}^{p} T(N_k) \text{ with } \sum_{k=1}^{p} N_k = N \tag{1}$$

We want to minimize the above time. Since $T(u)$ is convex,

$$T(u) \geq T\left(\frac{N}{p}\right) + \beta\left(u - \frac{N}{p}\right) \text{ where } \beta = T'\left(\frac{N}{p}\right)$$

thus

$$\begin{aligned} T &= \sum_{k=1}^{p} T(N_k) \geq \sum_{k=1}^{p} T\left(\frac{N}{p}\right) + \beta \sum_{k=1}^{p}\left(N_k - \frac{N}{p}\right) \\ &\geq pT\left(\frac{N}{p}\right) + \beta\left(\sum_{k=1}^{p} N_k - p\frac{N}{p}\right) \\ &\geq pT\left(\frac{N}{p}\right) + \beta(N - N) \end{aligned}$$

$$T \geq pT\left(\frac{N}{p}\right) \tag{2}$$

Thus, Eq. 2 shows us that, independently of the singulation algorithm used, the identification delay is minimized when

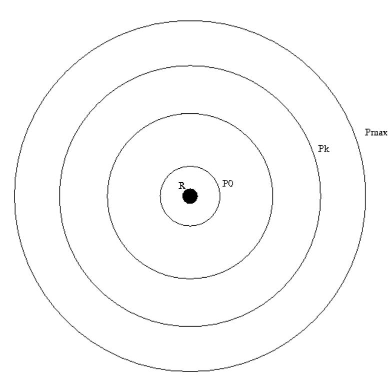


Fig. 1. Expanding horizon

we identify the same number of tags $\nu$ in each phase, thus for

$$N_k = \frac{N}{p} = \nu \quad (3)$$

where $p$ is the number of power levels used.

For example, when the tags are distributed on a grid

$$N_k = \pi(R_k^2 - R_{k-1}^2)d$$

where $d$ is the tags density.

Thus, Eq. 3 gives: $N_k = \pi(R_k^2 - R_{k-1}^2)d = \frac{N}{p}$ , thus $R_k^2 - R_{k-1}^2 = \frac{N}{\pi dp} = R$ Summing over $k$ gives us, since $R_0 = 0$ and $R_p = R_{max}$:

$$\pi R_{max}^2 d = N$$

Since $R_k^2 = kR = k\frac{R_{max}^2}{p}$

$$R_k = \sqrt{\frac{k}{p}} R_{max}$$

Assuming the standard path-loss model, we have $P_k = \alpha R_k^\delta$ with $\delta \geq 2$.

Which gives us:

$$P_k = \left(\frac{k}{p}\right)^{\delta/2} P_{max} \quad (4)$$

*E. Optimal number of power levels*

Now, let's find the optimal value for $p$.

From Eq. 2, the minimum achievable delay is

$$T_{min}(p) = pT\left(\frac{N}{p}\right)$$

From which we get

$$\arg\min_p \ T_{min}(p) = \arg\min_p \ ln\left(T_{min}(p)\right)$$

$$= \arg\min_p \ ln(p) + ln\left(T\left(\frac{N}{p}\right)\right)$$

Taking the derivative of the above expression gives:

$$\frac{d}{dp} ln(T_{min}(p)) = \frac{1}{p} - \frac{N}{p^2} \frac{T'\left(\frac{N}{p}\right)}{T\left(\frac{N}{p}\right)}$$

Setting it equal to zero gives:

$$p_{opt} - N \frac{T'\left(\frac{N}{p_{opt}}\right)}{T\left(\frac{N}{p_{opt}}\right)} = 0 \quad (5)$$

We get an interesting result if $T(u) = e^{\gamma u}$ (exponential complexity).

Then Eq. 5 (and this is indeed a minimum) gives us:

$$p_{opt} - N\gamma \frac{e^{\gamma \frac{N}{p_{opt}}}}{e^{\gamma \frac{N}{p_{opt}}}} = 0$$

which yields:

$$p_{opt} = \gamma N \quad (6)$$

So, the optimal level of power levels is proportional to the number of tags. Which gives us $T_{opt} = p_{opt} T\left(\frac{N}{p_{opt}}\right) = \gamma N T\left(\frac{N}{\gamma N}\right) = \gamma N e^{\gamma \frac{1}{\gamma}} = \gamma e N$.
We thus reduce from

$$T = e^{\gamma N}$$

to

$$T_{opt} = \gamma e N$$

In the general case, Eq. 5 doesn't have a solution $p_{opt}$. However, since $T$ is convex and non-decreasing on $[0, \infty)$, Eq. 2 is a decreasing function of $p$. But, since $T(0) \neq 0$ (it takes time to determine that there is no tag), increasing $p$ past $N$ will take more time ($N$ times $T(1)$, but also $p - N$ times $T(0)$). Thus, the optimal value when there is no solution to Eq. 5 if $p_{opt} = N$. This makes perfectly sense: the optimal expanding scheme is when wa manage to have only one tag at each power level.

But we have to remember that these are the theoretical limits one can achieve. In practice, we won't get such results because we're not capable to choose the $R_k$ such that $N_k = 1$ for all $k$. But just choosing a constant number of tags per power level $\nu$ ($p = N/\nu$) allows the complexity to go from

$$T = T(N)$$

to

$$T = \frac{N}{\nu} T\left(\frac{N}{N/\nu}\right) = \frac{N}{\nu} T(\nu) \quad (7)$$

Which is linear if $\nu$ is fixed. Thus, by choosing a number of power levels proportional to the number of tags, we always get a linear complexity. We will see later that one can dynamically adjust the power levels during the singulation process, which gives better performance.

A remark is in order here: the above results hold as long as the complexity considered is convex. While we often consider the average time complexity, this also holds for the worst-case complexity. And, while most singulation algorithms have a linear average complexity (and in the case of linear complexity we don't have any gain), worst-case complexities are often $\Omega(N)$. For example, Tree Walking Algorithms have worst-case complexities in $\Theta(NlnN)$. Thus, applying the above scheme reduces the worst-case complexity from $\Theta(NlnN)$ to $\Theta(N)$ (cf. Eq. 7).

Let's now have a look at the energy consumption, which is the main advantage of this scheme.

*F. Energy Consumption*

Since

$$E = \int_0^T P(t)dt$$

where $P$ is the power, we get:

$$E = \sum_{k=1}^{p} P_k T_k = \sum_{k=1}^{p} P_k T(N_k) \quad (8)$$

Let's have a look at this scheme and see how well it performs regarding energy consumption.

$$E = \sum_{k=1}^{p} P_k T(N_k) = \sum_{k=1}^{N/\nu} P_k T(\nu) = T(\nu) \sum_{k=1}^{N/\nu} P_k$$

Therefore, we have

$$E = T(\nu) \sum_{k=1}^{N/\nu} P_k \leq T(\nu) \sum_{k=1}^{N/\nu} P_{max} = \frac{N}{\nu} T(\nu) P_{max}$$

Thus, the energy consumption is reduced at least by the same factor as the time complexity (see Eq. 7). But in the previous inequality we used $P_k = P_{max}$ for all $k$, which is a really poor bound. In fact, we can get much better results, because, by definition the $P_k$ are smaller than $P_{max}$.

For example, let's see how our scheme performs in the case of tags distributed uniformly on a grid, when choosing power levels as in Eq. 4.

Assuming the standard path-loss model from Eq. 4, we have:

$$\begin{aligned} E &= T(\nu) \sum_{k=1}^{N/\nu} \alpha \left( \frac{k}{N/\nu} \right)^{\delta/2} R_{max}^{\delta} \\ &= \alpha R_{max}^{\delta} T(\nu) \sum_{k=1}^{N/\nu} \left( \frac{k}{N/\nu} \right)^{\delta/2} \end{aligned}$$

For large $p = N/\nu$, we have (see Appendix)

$$\sum_{k=1}^{N/\nu} \left( \frac{k}{N/\nu} \right)^{\delta/2} \sim \frac{N/\nu}{\delta/2+1} \quad (9)$$

This gives us

$$E = \alpha R_{max}^{\delta} T(\nu) \frac{N/\nu}{\delta/2+1} = P_{max} T(\nu) \frac{N/\nu}{\delta/2+1}$$

Thus, the energy consumption drops from:

$$E = T(N) P_{max}$$

to

$$E = \frac{N}{\nu} T(\nu) \frac{1}{\delta/2+1} P_{max}$$

Assuming a linear complexity, $\frac{N}{\nu} T(\nu) = T(N)$, we get

$$E = T(N) P_{max} \frac{1}{\delta/2+1} \quad (10)$$

Thus, the above scheme divides the energy consumed by a factor of $\delta/2+1$. For the common case where $\delta = 2$ or $\delta = 4$, we get a reduction by a factor of 2 or 3. In the case of a $\Omega(N)$ complexity (exponential for example), the savings are even greater. In fact, if the time is reduced by $\eta$, the energy consumption is reduced by $\eta(\delta/2+1)$.

### G. Finding the right expanding scheme

So far, we have evaluated the optimal time and energy savings one could get by using the optimal expanding scheme.

We have seen that, in the case of a regular distribution for the tags, there is a simple formula (Eq. 4). Here, we just assume that the number of tags in a certain area is proportional to the area.

If we read $N_k$ tags at phase $k$, with radius $R_k$, this means that the number of tags between $R_{k-1}$ and $R_k$ is $N_k$. For small $\delta R_i = R_i - R_{i-1}$, the density of tags within $R_k$ and $R_{k+1}$ will be close to the density of tags between $R_{k-1}$ and $R_k$. Thus, we have $N_k \approx d\pi(R_k^2 - R_{k-1}^2)$, and can choose $R_{k+1}$ such that $\bar{N}_{k+1} = d\pi(R_{k+1}^2 - R_k^2)$, where $\bar{N}_{k+1}$ is the number of tags we want to have at phase $k+1$, which is, from what we've seen, $\bar{N}_{k+1} = \frac{N}{p} = \nu$.

Thus, we get that

$$R_{k+1}^2 - R_k^2 = \frac{\nu(R_k^2 - R_{k-1}^2)}{N_k} \text{ for } N_k \neq 0$$

so

$$R_{k+1} = \sqrt{\frac{R_k^2 + \nu(R_k^2 - R_{k-1}^2)}{N_k}} \text{ for } N_k \neq 0 \quad (11)$$

Assuming the standard path-loss model:

$$P_{k+1} = \left( \frac{P_k^{2/\delta} + \nu(P_k^{2/\delta} - P_{k-1}^{2/\delta})}{N_k} \right)^{\delta/2} \quad \text{for } N_k \neq 0$$

Now, Eq. 11 obviously doesn't hold for $N_k = 0$. If we read no tag at phase $k$, one good policy would be to double the area covered, thus choose $R_{k+1}^2 - R_k^2 = 2(R_k^2 - R_{k-1}^2)$, or

$$R_{k+1} = \sqrt{3R_k^2 - 2R_{k-1}^2}$$

Which gives us:

$$P_{k+1} = \left( 3P_k^{2/\delta} - 2P_{k-1}^{2/\delta} \right)^{\delta/2}$$

For the initial value, one could choose $R_0 = \frac{R_{max}}{p}$, or $P_0 = \frac{P_{max}}{p^{\delta}}$

In summary, what this scheme does is that it dynamically selects the next power level in order to have a fixed number $\nu$ of tags read at each power level.

## II. Capture Effect

### A. Background

Research has yielded very efficient algorithms in the single reader case, letting very little room for improvement. However, this is not the case for the multiple readers case. One of the major problem one encounters is the reader collision problem: when a tag is in the vicinity of multiple readers (we will refer to these zones as collision zones), it won't be read if the readers run are the same time, because of interferences at the tag. Many papers addressed this issue, and developped different schemes mostly based on TDMA to avoid the reader collisions problem [7], [8]. Our approach

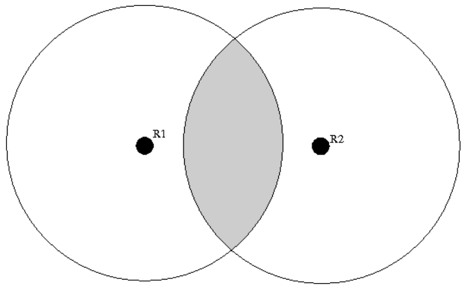


Fig. 2. The grey are denotes the collision zone

was different. Instead of considering that a tag in reading range of two or more readers won't be read, we have a more optimistic approach taking into account the capture effect, and the level of interferences at the tags. We then developped a very simple scheme exploiting this fact, which outperformed by a factor of 2 to 3 the pure TDMA schemes in our simulations. We think that our scheme is especially relevant since recent advances in RFID hardware yielded devices with low SNR requirements, making TDMA-based approaches less and less relevant.

### B. The Problem with TDMA

The most common scheme used to avoid reader collision is TDMA, in which each reader runs one after another: by avoiding simultaneous transmissions, we make sure that all tags will be read. However, there are two main problems with pure TDMA. First, there is the problem of finding the right synchronization scheme [7]: by devoting too many slots, the performance gets reduced. By devoting too few slots, we have the risk of collisions. Second, and more importantly, TDMA is inherently inefficient in this case. To see this, let's have a look at Fig. 2.

Let $N$ be the total number of tags, $N_{coll}$ the number of tags inside the collision zone. If we use pure TDMA, alternating between the two readers, each will read $\frac{N}{2}$ tags[2] (assuming a symmetrical repartition), but at a speed half of the speed a single reader could read. Thus, the time taken is $T = 2T\left(\frac{N}{2}\right)$. Assuming a linear complexity, we get $T = T(N)$.

Thus, we end up reading the tags at a rate that could be achieved by a single reader, which is probably not optimal.

### C. Parallel Reading

Now, let's assume the following: the two readers run in parallel. The tags in the collision zone won't be read because of interferences. So how do we read them? The idea is just that as soon as a reader is done reading the tags it could read (and there are $\frac{N-N_{coll}}{2}$ such tags), it shuts down. Let's pretend that $R_1$ finishes first. Then, the other reader $R_2$ finishes reading all the remaining tags that couldn't be read because of the interferences caused by $R_1$. What time does this take?

[2]We assume that a tag that has been read by a reader won't be read by the other one.

It takes the time taken by $R_2$ to read its $\frac{N-N_{coll}}{2}$ tags, plus the time to read $N_{coll}$ tags. But, contrarily to TDMA, the readers run a full rate, and not half rate. Thus, we get:

$$T = T\left(\frac{N - N_{coll}}{2}\right) + T(N_{coll})$$

Assuming a linear complexity, we get:

$$T = T\left(\frac{N + N_{coll}}{2}\right)$$

Since $N_{coll} \leq N$,

$$T\left(\frac{N + N_{coll}}{2}\right) \leq T(N)$$

More precisely, the smaller $N_{coll}$, the greater the gain. This approach can be used with more than two readers, as we'll see.

### D. Interference Zones

The above approach could possibly miss some tags. The reason is as follows: in the literature, it is said that when tags are in the reading range of two or more readers, they won't be read due to collisions. But actually, it's slightly more complicated than that: a tag which is within reading range of one reader won't be read due to interference if it is close enough to another reader so that the interference posed by this other reader at the tag is high enough. The point is that *the tag doesn't have to be within reading range of the second reader to be in a collision zone*. What does this change?

First, the collisions zone are actually wider that the above circles suggest. They are not bounded by the intersection of readers' reading range. More precisely, the lower the path-loss, the bigger the difference between the two models will be.

Second, and more importantly, this implies an asymmetry in the reader collision problem. Asymmetry in the sense that *a tag that is in the interference zone between two readers cannot necessarily be read by both readers*. As far as we know, this fact isn't taken into account by any load-balancing or redundant-reader elimination algorithm. They often assume that a tag in a collision zone can be read indifferently by both readers.

### E. Proposed scheme

The solution to avoid missing tags is thus the use of a pure TDMA, but only once parallel reading cannot read any more tag.

The algorithm is simply:

1) proceed to a parallel reading: all the readers proceed to a reading cycle at the same time. As soon as a reader has read all the tags it could read, it goes to a standby state
2) when the parallel reading is finished (the last reader stops), use pure TDMA between all the readers to read the remaining tags

The parallel reading phase allows a maximum spatial reuse, and thus a better reading rate. The pure TDMA phase ensures that we do not miss any tag.

### F. Capture Effect

Before analysing the results of the above scheme, let's have a look at the reason motivating this approach, the capture effect.

Very few - if any - work has addressed the impact of the capture effect in RFID systems. Many papers just consider that if a tag is in vicinity of 2 readers, then it won't be read due to collisions. As we have seen in the previous section, this is very simplistic, since even tags in the reading range of only one reader can possibly not be read to due interferences. Furthermore, it ignores an important effect, the capture effect. Basically, the capture effect is the phenomenon where a signal can be received inspite of the interference. This is something we observe everyday: we are able to understand someone speaking inspite of the surrounding noise, another conversation going on a few meters away, etc.

What that means, in our case, is that the reader collision problem may not be as bad as it seems. Even if we are in a collision zone, we may be able to read some tags, provided that the interference level at this point of space is not too high. Thus, parallel reading is likely to help, because many tags inside the collisions zones can be read in parallel, and don't need TDMA.

### G. Simulation results

The simulations have been run under rfidsim, a custom rfid-oriented network simulator developped at the University Of Illinois At Urbana-Champaign. The simulator is written in C++, implements several propagation models (free space, two-ray, etc) and different fading models (Ricean, Rayleigh), handles multiple interfaces per nodes, multiple channels, active and passive tags, etc. For the simulations below, we implemented a simplified version of the Class I Gen 2 specification singulation protocol. One important parameter was the capture threshold, i.e. the minimum SINR required for a transmission to succeed. We used 3 different values: 10dB (very conservative value, used by ns-2 in 802.11 simulation code), 6 dB, and 3dB. All these values are still much higher than the theoretical value computed from Shannon formula[3]. We used a uniform random distribution for the tags, a uniform distribution for the readers, in an area of 6 by 6 meters.

Fig. 3 compares the singulation time as a function of the number of tags for pure-TDMA and our scheme, for 2 readers, and population of tags uniformly distributed. We can see that even in the worst case (high capture threshold), our scheme (denoted as PARA) surpasses TDMA.

Fig. 4 is the same, except that this time we consider 4 readers. Here, the gains are even greater. We also notice that the savings vary sensibly with the capture threshold used.

Fig. 5 shows the number of tags read as a function of time (population of 680 tags uniformly distributed), for pure TDMA and our scheme. As we can see, contrarily to the TDMA approach, the reading rate is not constant. We first start off with all the readers running in parallel, reading as many tags as possible, and then their number slowly decreases, as they shut down one after another, until the TDMA phase.

[3]RFID use a very low bitrate, which explains a low required SINR.

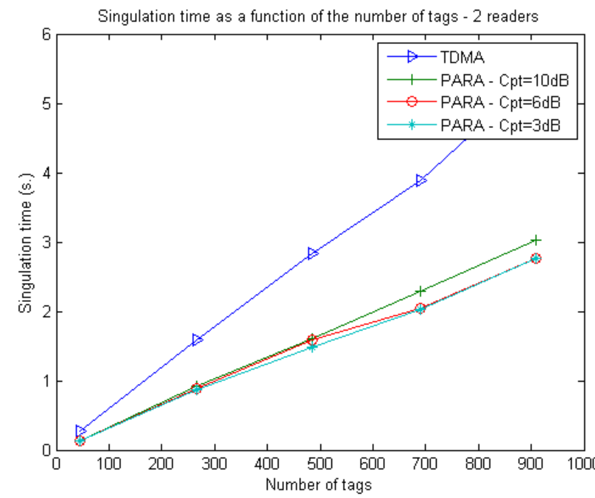


Fig. 3. Singulation time as a function of the number of tags - 2 readers. Comparison of TDMA and our scheme (PARA), for different capture thresholds (Cpt)

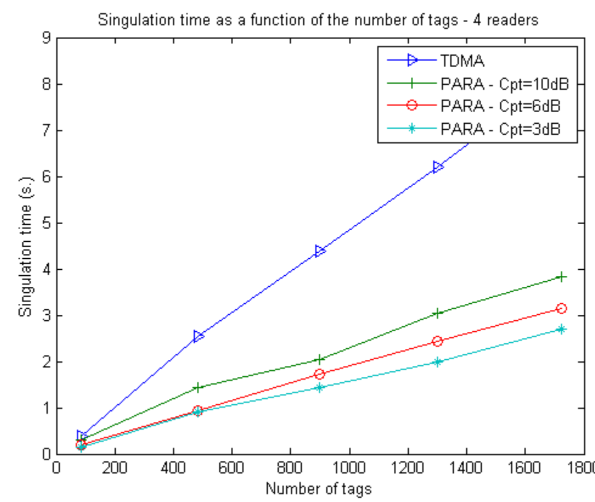


Fig. 4. Singulation time as a function of the number of tags - 4 readers. Comparison of TDMA and our scheme (PARA), for different capture thresholds (Cpt)

These simulations confirm an obvious fact: the smaller the capture threshold, the more effective is our scheme (since more tags can be read during the parallel phase).

## III. Conclusion

We presented two schemes to reduce energy consumption and singulation delay in RFID systems.

Expanding horizon is a very simple yet effective way to reduce energy consumption. The singulation delay can also be reduced, in the case where the singulation protocol is over-linear (worst-case for a TWA for example). The main

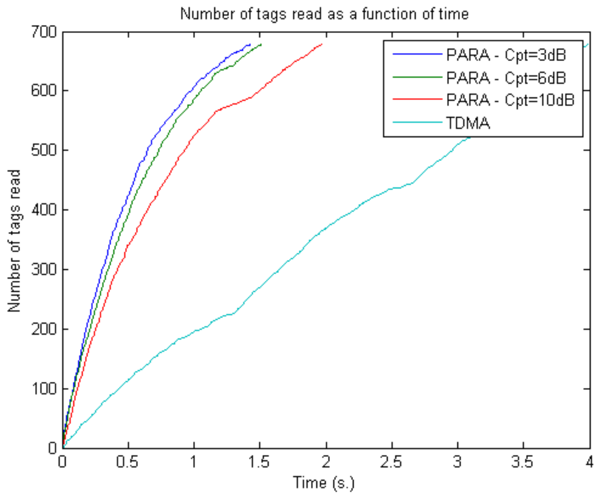


Fig. 5. Number of tags read as a function of time - 4 readers. Comparison of TDMA and our scheme (PARA), for different capture thresholds (Cpt)

idea is that this form of power control achieves a form *spatial singulation*, splitting the population of tags into smaller sets.

Then, we presented a very simple yet very effective scheme to reduce the singulation delay in the case of multiple readers, exploiting the capture effect. It has the advantage of simplicity, and doesn't require any complicated algorithm to assign tags to readers. We furthermore highlighted the important distinction between intersection of reading zone and interference zone, distinction never made in the literature, and that breaks the symmetry used in several partitioning algorithms. Finally, we evoked the importance of the capture effect in RFID systems, importance which is growing since recent research in hardware design drastically decreased the threshold requirements, and thus makes TDMA based approach less and less relevant.

## Appendix
## Proof of Eq. 9

We start with

$$S = \sum_{k=1}^{N/\nu} \left(\frac{k}{N/\nu}\right)^{\delta/2} = \left(\frac{1}{N/\nu}\right)^{\delta/2} \sum_{k=1}^{N/\nu} k^{\delta/2}$$

Which can be rewritten as

$$S = \left(\frac{1}{m}\right)^{n} \sum_{k=1}^{m} k^{n} \quad \text{for} \quad n = \delta/2 \quad \text{and} \quad m = N/\nu$$

Faulhaber's formula tells us that

$$\sum_{k=1}^{m} k^{n} = \frac{1}{n+1} \sum_{k=0}^{n} \binom{n+1}{k} B_k m^{n+1-k}$$

where $B_k$ is the k-th Bernoulli's number.
Thus,

$$S = \left(\frac{1}{m-1}\right)^{n} \frac{1}{n+1} \sum_{k=0}^{n} \binom{n+1}{k} B_k m^{n+1-k}$$

Which is equivalent, as $m$ goes to infinity, to

$$\left(\frac{1}{m}\right)^{n} \frac{1}{n+1} \binom{n+1}{0} B_0 m^{n+1}$$

Since $\binom{n+1}{0} = 1$ and $B_0 = 1$, this gives us

$$S \sim \frac{m}{n+1}$$

Substituting $n = \delta/2$ and $m = N/\nu$, we finally get:

$$S \sim \frac{N/\nu}{\delta/2 + 1} \quad \text{for} \quad p = N/\nu \quad \text{large}$$

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