# Comparison of Transmission Schemes for Framed ALOHA based RFID Protocols

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## Abstract

*The performance of RFID anti-collision protocols that are based on framed ALOHA depends on a transmission scheme that controls access to the shared channel. In this paper, we outline the characteristics of the RFID domain that impact the performance of such transmission schemes and compare four different transmission strategies. A novel technique introduced in this paper that recursively estimates the backlog on a slot-by-slot basis exhibits a superior performance in our simulations. The results also illustrate that our implementation of the Q algorithm proposed in [2] only performs well, if the frame size changes are restricted to incremental updates.*

## 1 Introduction

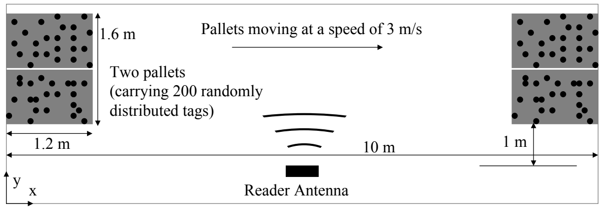
As the number of RFID tags that are simultaneously present in the range of a reader increases, high identification rates will become essential to prevent missed reads and long delays. A variety of approaches to improve the speed at which RFID tags are being identified exist today. Most of them target the physical and medium access control layer of RFID communication protocols. Examples include increased data rates due to more efficient spectrum usage on the physical layer and various different so-called anti-collision algorithms that control access to the shared radio channel. The EPCglobal UHF Class 1 Generation 2 protocol [2] that we consider in this paper uses an algorithm to singulate individual tags which is based on framed ALOHA. In framed ALOHA, a transmission node that has a packet to transmit selects at random one of the time slots of a frame [8]. The achievable throughput depends on a transmission scheme that controls the broadcast probability of the tags by adjusting the number of time slots in a frame accordingly. Since the true number of tags powered and ready to transmit is usually unknown, the transmission control strategy used by the reader needs to estimate the true number of tags and then transmit the corresponding broadcast probability – encoded in the frame size – to the tags.

The main contribution of this paper is a comparison of three existing transmission control strategies to a novel scheme proposed in this paper. We show how the characteristics of the UHF RFID domain impact the performance of the different schemes and analyze their strength and weaknesses. We also use simulation results to evaluate the different schemes in a typical RFID supply chain application.

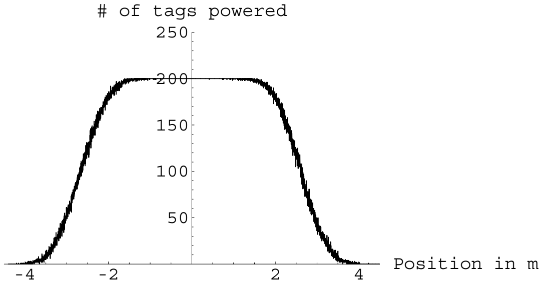
## 2 RFID Characteristics

RFID technology presents some interesting wireless networking problems due to the unusual traffic characteristics and the limited resources of the transmitting nodes – the RFID tags. Before we introduce various transmission control strategies in the following section, we will discuss these properties in more detail here.

In supply chain management, RFID systems are often used to automate the identification of cases and single items on a pallet or on a conveyor belt. In both cases the tagged objects are moved past an RFID antenna at a constant speed (cf. Figure 1(a)). If the read range of the reader is well-defined such as for HF or LF RFID systems, the number of tags within range will monotonically increase, until all tags are powered. For RFID systems that operate at UHF frequencies, the situation is more complicated. Since RFID systems are usually deployed indoors, the strong fading component characteristic for indoor wireless channels in this frequency band [6] leads to frequent field nulls. Since tags do not carry a battery, they will frequently loose power and possibly also their state, as they move past the reader. This has been illustrated in [4, 5]. Figure 1(b) shows the results of a simulation as a pallet carrying 200 tags is moved past a reader in the dock door application of Figure 1(a).



(a) Loading dock application



(b) Simulated arrival pattern

**Figure 1. Simulated arrival pattern for a loading dock scenario.**

| Parameter Name | Value |
|---|---|
| Path Loss Exponent | 2 |
| Rician factor | 6 dB |
| Reader power (EIRP) | 3300 mW |
| Reader antenna 3dB beamwidth | $60^o$ |
| Reader capture ratio | 32 dB |
| Reader sensitivity | -80 dBm |
| Minimum tag input power | -15.22 dBm |
| Tag backscatter factor | 0.25 |
| BER | $10^{-3}$ |

**Table 1. Simulation parameters.**

The multipath fading is modeled statistically by a Rician distribution, which is commonly used to describe the small-scale fading envelope, when there is a strong line-of-sight component [6]. The other simulation parameters are listed in Table 1. The simulation shows that tags frequently power up and power down as they approach the reader antenna. The above simulation is somewhat of a simplification of the real world, since the material stored on the pallet and the tag antenna orientations are not taken into account, although they will considerably influence the power received by the microchip of the tag. The result illustrates however the traffic characteristics transmission control schemes need to consider to efficiently control the broadcast probability: The evolution of the number of tags powered and ready to transmit over time is highly application-specific, instantaneous arrival rates vary significantly due to the frequent field nulls, and backlogged tags can "depart" without ever having successfully transmitted their data.

The RFID domain does not only introduce unusual traffic characteristics, the medium access protocol used in the particular RFID protocol considered in this paper (EPCglobal UHF Generation 2 Class 1 protocol) also differs from the framed ALOHA commonly described in the networking literature [8] in a number of ways. To reduce the complexity of the tags, the available frame sizes are limited to powers of two. This results in a reduction in the maximum throughput to $35\%$ from the maximum of $e^{-1} = 0.368$ for some tag estimates.

Framed ALOHA is also only used as the contention mode for short packets that reserve longer noncontending slots for the transmission of the longer unique tag ID. The use of such a reservation system is a common way to substantially improve the throughput of multiaccess channels [1]. We assume here that tag ID packets require one time unit each for transmission and that reservation packets require $\nu = 1/8$ units (neglecting overheads of reader commands and turn-around-times). According to [1], the maximal throughput $U$ in tag IDs per time unit achievable in such a scheme is then given by the following equation, where $U_r = e^{-1}$ represents the maximum throughput of framed ALOHA:

$$U = \frac{1}{1 + \frac{\nu}{U_r}} \approx 0.75 \qquad (1)$$

Framed ALOHA usually means that acknowledgements are only sent after the end of each frame. This is however not true for the case of the RFID protocol discussed here. As outlined in [2], there is a reader command after each slot. Transmission control schemes consequently do not have to wait until the end of frame to change broadcast probabilities by setting the appropriate frame size. They can simply cancel a running frame and initiate a new one.

## 3 Transmission control schemes for framed ALOHA based RFID protocols

In the previous section we outlined characteristics of RFID that influence the performance of transmission schemes that control access to the shared channel. In this section we will outline four different transmission schemes. The first two approaches we present evaluate the evidence from the reader at the end of the frame, while the latter two can evaluate the feedback from the reader on a slot-by-slot basis and possibly interrupt a current frame to choose a different frame size. The first three schemes are based on earlier work; the fourth approach is a novel method presented in this paper. In the following analysis, let $S$ and $C$ denote random variables indicating the number of single reply and collision slots in a single frame with $L$ slots and $N$ tags.

### 3.1 Frame size updating after Schoute

In [8], Schoute developed a backlog estimation technique for framed ALOHA that is exact under the assumption that the frame size is chosen so that the number of stations that transmit in each time slot is Poisson distributed with mean 1. The backlog after the current frame is then simply given by $B_t = 2.39c$.

### 3.2 Bayesian frame size updating

In [3], a transmission scheme was presented that does not rely on the Poisson assumption used by Schoute. It estimates the number of tags $N$ present at time $t$ given the feedback from the current frame, i.e., the number of collisions, single replies and empty slots. This estimated backlog is then updated given the number of successful transmissions. The algorithm simply chooses the frame size $L$ that maximizes the expected throughput $U$ for the consecutive frame. To consider the unknown distribution of arriving and departing tags characteristic for UHF RFID systems, we do not take the past observations from previous frames into account. This is equivalent to assuming that new tags arrive and depart according to a uniform distribution.

### 3.3 Slot-count (Q) algorithm

The Q Algorithm defined in [2] keeps a floating point representation of the current frame size exponent $Q_{fp}$, which is incremented by a constant $\beta$ whenever a collision occurs and decremented by $\beta$ whenever an empty slot is detected. A successful slot leaves $Q_{fp}$ unchanged. The current tag estimate $2^{Q_{fp}}$ is thus updated by multiplication or division with $2^{\beta}$ depending on the outcome of slot. $\beta$ is set to $0.1 \leq \beta \leq 0.5$ and according to [2] a reader should use small values of $\beta$ when $Q$ is large, and larger values of $\beta$ when $Q$ is small. Based on empirical results, we chose to set $\beta = 0.8/Q$. At the end of the frame or if $Q_{fp}$ is updated on a slot-by-slot basis, the new frame is initiated with a size of $2^{round(Q_{fp})}$.

### 3.4 Bayesian slot-by-slot updating

In this subsection we present a novel transmission control strategy that evaluates the current frame size as the frame progresses. The individual steps of the broadcast scheme are adapted from [7] to suit the nature of framed Aloha in RFID: (1.) Compute the frame length $L$ based on $Pr(N)$. (2.) Start frame with $L$ slots and wait for tag replies. (3.) Update $Pr(N)$ based on evidence from the reader at the end of each slot. (4.) Adjust $Pr(N)$ for tags that are departing during the current frame because they lost power. (5.) If frame length $L$ given $Pr(N)$ is optimal, continue with the next slot and go back to step 3. Otherwise, cancel current frame. (6.) Adjust $Pr(N)$ by considering the arrival of "new" tags.

The number of tags powered in step 3 of the above scheme is estimated using the conditional tag number probability distribution, given all past observations. According to Bayes rule, the probability that n tags are powered and ready to transmit in the current frame at a time $t$, given all evidence $z_{1:t}$ including the evidence from the last slot, is given by:

$$Pr(N_t|z_{1:t}) = \alpha Pr(N_t|z_{1:t-1}) \cdot Pr(z_t|N_t)$$

For a slot that is observed to be empty, $Pr(z_t|N_t)$ is then given by

$$Pr(z_t|N_t) = \sum_{i=0}^{r}(1 - \frac{1}{L - L_j})^{r-i} \cdot Pr(I = i|R, C)$$

where $R = N - 2C - S$ and denotes a random variable representing the maximum possible number of tags that have not responded in the previous $L_j$ slots. $I$ denotes a random variable representing the number of tags that were involved in the $c$ collisions slots of the current frame in addition to the "mandatory" $2c$ tags. The conditional probability distribution of $Pr(I = i|R, C)$ is simply given by

$$Pr(I = i|R, C) = \binom{r}{i} p^i (1 - p)^{r-i}$$

with $p = c/(L - L_j + c)$. The computation of $Pr(z_t|N_t)$ for slots that featured a single reply or a collision follows the same principle.

## 4 Evaluation

This section evaluates the transmission control schemes presented in the previous section. The characteristics of the RFID domain outlined in Section 2 suggest that a transmission scheme is desirable that can interrupt a running frame, if the current frame size is considered non-optimal. Although frame-based methods such as the first two approaches discussed in the previous section provide good backlog estimates based on the number of tags that replied in the previous frame, the arriving and departing tags caused by the frequent field nulls and tag movements themselves will significantly increase the uncertainty about the true number of tags ready to reply in the next frame. The two transmission control strategies that are capable of evaluating the evidence online on a slot-by-slot basis will provide a better throughput because they cancel a frame, once they realize that the original estimate was not correct. While the $Q$ algorithm requires only modest computational resources,

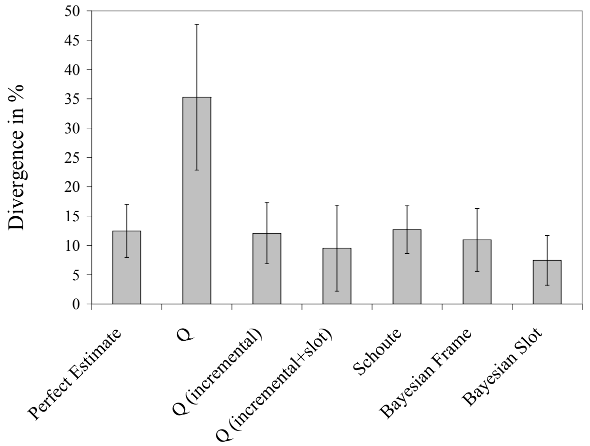


**Figure 2. Divergence of the simulated throughput from the theoretical maximum for the different schemes.**

it does not specify the crucial control parameter $\beta$. Since this parameter depends on the certainty of the current estimate, the current frame size and the number of tags present, its choice is not trivial. A value of $\beta$ that is chosen too large will lead to significant overshoots, while a $\beta$ that is too small will reduce the swiftness of a response to a change. The Bayesian algorithm that updates the tag probability distribution in an recursive manner slot-by-slot does not suffer from this weakness. It requires however significant computing resources, although a large part of the computations can be precomputed and stored in the memory of the reader device. The Bayesian frame updating approach will only provide a better estimate than the Schoute approach, if the Poisson condition is not met – the ratio of tags $N$ to slots $L$ is larger than 1. We will now use the simulation scenario of Section 2 to evaluate the performance of the four different transmission strategies quantitatively. Two pallets carrying 200 tags are moved past an antenna and the transmission control strategy changes the frame size accordingly, until all 200 tags are identified. The different transmission schemes are compared to what we termed the "perfect estimate". This transmission scheme knows at the end of each frame exactly how many tags responded in the last frame and chooses the next frame size accordingly. The divergence from the theoretical maximum throughput evident in Figure 2 results from the unknown number of newly arriving and departing tags in the consecutive frame. The simulation results also show that the performance of the Bayesian frame update algorithm is essentially the same as the perfect estimator. Its throughput is $11\%$ below the maximum theoretical throughput of framed ALOHA. Given its simplicity, the modified transmission scheme based on the work by Schoute also performs well.

The performance of the $Q$ algorithm is poor given our choice of the constant $\beta = 0.8/Q$. The performance can however be significantly improved, when changes to $Q$ are restricted to incremental changes (denoted (incremental) in Figure 2). Under these conditions the oscillations of the $Q$ algorithm are damped and the simulated throughput is similar to the other frame-based transmission schemes. We will obtain an even better performance with the Q algorithm in our simulations, if we apply it on a slot-by-slot basis and restrict it to incremental changes. The Bayesian scheme that updates the probability distribution of tags ready to reply after every slot achieves the highest throughput ($34\%$ on average). According to Eqn. 1 this leads to an overall throughput of the reservation system of $73\%$. This superior performance is explained by the fact that this algorithm can effectively take into account arriving and departing tags, before the end of the frame and boost the performance consequently.

## 5 Conclusion

In this paper, we evaluate four different transmission control strategies for RFID anti-collision protocols based on framed ALOHA. The simulation results indicate that a novel transmission scheme proposed in this paper that specifically addresses the characteristics of UHF RFID can achieve a throughput of 34% under the simulated test conditions for the framed ALOHA contention mode. Our analysis also shows that backlog estimates based on a Bayesian approach and a Poisson approximation provide adequate results in an RFID environment, while our implementation of the $Q$ algorithm defined in [2] only performs well, if the frame size changes are restricted to incremental updates.

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