0.469 PDFSA protocol for RFID Arbitration

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***Abstract*—To enhance the performance of the Dynamic Frame Aloha protocol for RFID arbitration, the grouping of the tag population has been suggested in past works. However, none of them has formalized the problem of optimizing such grouping, nor has been able to provide an efficiency much higher than 0.367, the classic DF-Aloha maximum performance. In this paper we explain how to set the optimal size of groups, based on results attained decades ago in random access systems. We then present a novel protocol, Partitioned Dynamic Frame Slotted Aloha (PDFSA), based on grouping, that, when adopting the best estimation mechanism, reaches an asymptotical efficiency up to 0.469. With a more practical estimate and a short initial phase, this protocol provides an efficiency above 0.420 for any value of the population size N, reaching 0.455 asymptotically.**

I. Introduction

Radio Frequency Identification (RFID) is an automatic identification system where a reader interrogates a set of tags in order to identify each of them [1]. Here collisions occur among the responses of tags and a Collision Arbitration Protocol must be used to arbitrate collisions so that all tags can be finally identified.

Collision Arbitration Protocols (CAP) for RFID can be broadly classified in the Dynamic Frame Aloha family and in the Tree family. Dynamic Frame Aloha (DF-Aloha) was first proposed by Schoute for satellite communications [2]. Here, time is subdivided into time slots equal to a packet transmission time, and slots are grouped into frames. The difference with respect to Slotted Aloha (S-Aloha) is that a terminal is permitted to transmit only one packet per frame, in a randomly chosen slot, and that only terminals that have collided in the preceding frame can re-schedule their transmission in the current frame. In [2] channel feedback is used to get an estimate of the backlog size n at the end of the previous frame, given by $\hat{n} = \text{round}(2.39c)$, where c is the number of slots collided in the same frame. The protocol is then stabilized by setting the frame length r equal to the backlog estimate. This protocol, under Poisson arrivals, has been shown to provide a throughput equal to $\mathbf{0.421}$ pkt/slot.

On the other side, tree-based protocols have appeared in 1979 [3][4] for random access systems. Here, colliding terminals are successively split into sub-groups in such a way that, in the end, each sub-group is composed of a single tag only, thus ensuring collision-free transmission. The simplest tree-based protocol yields a throughput equal to $\mathbf{0.347}$ pkt/slot, under Poisson arrivals [3]. Improvements have been proposed in [4] [5] to produce the most efficient protocol up to date, the Gallager-Tsybakov protocol, which reaches a throughput equal to $\mathbf{0.487}$ pkt/slot.

Both protocol families have also been considered in RFID [1], where Schoute's DF-Slotted-Aloha is referred to as DFSA. Here, rather than throughput, we may more exactly use the term "efficiency", being the efficiency defined as

$$\eta_N = N/L(N),$$

where N is the tag population size and $L(N)$ is the average number of slots needed to identify all tags.

Many papers dealing with DF-Aloha investigate backlog-estimation and frame-setting problems. In the ideal case when the backlog size n is known, the optimal frame-length setting is $r = n$, and the maximum achievable throughput is $e^{-1} \simeq 0.367$. In most cases the estimates proposed in literature approach the theoretical maximum, but this happens for a limited range of N, because of the mismatch that occurs when the initial estimate $\hat{N}$ differs from the population size N (see for example [6]).

Tree algorithms also have been proposed for RFID [1]. In particular in [7] it is shown how these can be used to provide efficiency $\mathbf{0.487}$, the same observed in the Gallager-Tsybakov. In the RFID environment, however, where the protocol is operated centrally by the reader and tags have very little processing capability, the two families have different impact on the overhead and robustness of the mechanism. As a consequence, the theoretical advantage of tree algorithms over DF-Aloha is no longer granted. This has probably favoured the choice of DF-Aloha as preferred protocol in many implementations [8][9].

In the last decade many variants on the two protocol families cited above have appeared in literature. Some deals with the estimation phase, others with the collision resolution phase, suggesting even hybrid mechanisms that mix vantages (or disadvantages) of the two families. Lack of space prevent us from discussing here these solutions, some of which are reported in [1]. In the present paper we only consider the specific modification of DF-Aloha that recently has been referred to as "grouping", i.e., the feature that subdivides the population into small groups so that the use of DF-Aloha is more efficient. A detailed discussion of the relevant literature on grouping is given the next section.

This work presents three new contributions. The first contribution explains how to set the optimal size of groups referring to results attained decades ago in random access systems. We then propose a novel protocol, Partitioned Dynamic Frame Slotted Aloha (PDFSA), that, during the identification phase, operates a partition of the tag backlog in an optimal way. Its performance depends on the performance of the backlog estimation mechanism adopted, that can be any of the many proposal appeared in literature. We show that, adopting the best estimation mechanism proposed up to now, the asymptotical efficiency rises to $\mathbf{0.469}$. Furthermore, we show that, adopting a practical estimation mechanism proposed in [10], and an additional rough estimation phase used at the beginning, efficiency of PDFSA is maintained above 0.420 for any value of the population size N, reaching $\mathbf{0.455}$ asymptotically, a performance, to our knowledge, never observed in RFID systems.

The paper is organized as follows. In Section II, we discuss the literature that is relevant to our work. In Section III we refresh some results on DF-Aloha and different estimates, and finally in Section IV we introduce the new protocol. Our concluding remarks are reported in Section V.

II. Related work

Apparently, grouping has been discovered in [11]. The protocol proposed, EDFSA, uses grouping to cope with large population size in presence of limitation in the frame length. Authors do not discuss the influence of the tag group sizes on the throughput, which is still below 0.39.

In [12], the protocol proposed, GBBSA, assumes the physical capability of receiving the bit of newly introduced reservation sequences, even when colliding. To improve the performance of grouping, tags are allowed to transmit according to a probability that is dynamically set. The throughput is very high, owing to the aforementioned assumption. However, authors do not discuss the influence of the group size on the throughput.

In [13], after an initial subdivision, the information attained in identifying the first group is used to modify the other groups. A discussion is provided about optimal partitioning; however, no explicit form solution is provided for optimal partitioning. The efficiency of the proposed protocol is still below 0.39.

In [6], the proposed algorithm, CGA, uses iterations each composed of two phases. In the first phase the estimate of the remaining backlog size is performed, while in the second phase only a subset of the backlog is enabled to respond. The groups, composed of tags that collide in the same slot, form and change in size as the protocol proceeds. The operation requires two commands and a 128 bit word to be sent to tags. However, CGA, can not provide a throughput higher than 0.368.

The work of Wang and Lee [14] is close to the work in [13], and is the one that is most closely related to our work. Therefore, we consider it in detail. The authors clearly state, apparently for the first time, that grouping can take advantage of the higher throughput presented by smaller groups. Their protocol, GB-DFSA, presents two phases; in the first phase the reader estimates the number of tag groups by some frames of probing that evaluate the backlog size as $2.39c$, where c is the number of collided slots. In the second phase, the identification phase, the protocol "first distinguishes all tags into s groups." Then groups are identified using DFSA. According to the parameters that provide best results, the protocol uses groups that do not exceed 8 tags (estimated) and probing-frame length of 4 slots. The efficiency attained by simulating GB-DFSA is shown to be slightly better than 0.4 for a number of tags from 200 to 2000, the best performance if compared to the protocol in [13]. However, from the protocol point of view, it is not clear how GB-DFSA can address only the tags within a group in the identification phase. Since this may influence robustness and protocol overhead, we can not take for granted the performance indicated. Furthermore, the mechanism that determines the group size appears rather empirical, since no discussion is provided about its optimal choice.

As a comment on the cited works on grouping, and as an introduction to ours, which still is based on grouping, we must note that:

- the convenience of subdividing the original population into smaller sub-groups is known since the appearance of tree algorithms in 1979 [3]. Here, in fact, Capetanakis shows that binary splitting is convenient if the population size has an average below 1.70; otherwise it is convenient to split the population into groups of such size in the average;
- in tree protocols for random access systems the average of the distribution of the population size can be chosen in such a way as to maximize throughput [5]; in fact, the optimal choice of the average population size is close to 1 [5]. For example it is 1.266 for the Gallager-Tsybakov protocol;
- in DF-Aloha protocols the throughput related to optimized Poisson distribution is much higher than the S-Aloha limit 0.367, being, for example, 0.421 for Schoute's DFSA (see the following section);
- a random partition of a population yields groups that are binomially distributed, i.e., Poisson distributed when the original population size is large and groups are numerous.

The observations above show that grouping is advantageous and that results on random access derived decades ago are directly re-applicable to RFID. For example, referring to the cases explored in [13] and [14], one can expect that, adopting DF-Aloha with Schoute's estimate (DFSA) for solving groups, the efficiency can reach 0.421 with an average number of tags per group equal to 1.11. However, one can use tree protocols as well, attaining for example 0.487 with Gallager-Tsybakov [7].

III. Poisson Population

Here we briefly recall some results on DF-Aloha, published in [10], which refer the efficiency of DF-Aloha under different estimation mechanisms and frame setting policies. The population is assumed to be Poisson distributed with an average γ that can be chosen in order to maximize the efficiency. This scenario is the one assumed in random access systems and its results can be straightforwardly used to evaluate the performance of grouping in RFID, as explained in the previous section. We only report results with some explanations. The reader interested in the evaluations details is referred to [10].

Table I
Throughput of a Poisson population for different backlog estimates.

	Schoute	Bayesian	Optimum	Ideal
γ_{opt}	1.11	1.11	1.12	1.24
η_{opt}	0.4271	0.4271	0.4275	0.4377

Table II
Throughput of a Poisson population with average γ, and frame restart.

	BLB	Bayesian	Optimum LB	Optimum UB	ideal
γ	1.19	1.18	1.2	1.2	1.51
η_{opt}	0.4583	0.4687	0.4693	0.4739	0.515

The throughput is evaluated as:

$$\eta_\gamma = \frac{\gamma}{\sum_{n=0}^{\infty} \frac{\gamma^n}{n!} e^{-\gamma} L(n)}, \qquad (1)$$

where $L(n)$ is the average length of the identification period with a population size $N = n$.

We first consider the case where the frame is entirely explored. When not specified otherwise, in the following we assume that the frame length is set equal to the estimate of the remaining backlog size.

In Table I we report the optimum γ and throughput with Poisson distribution (1) for different estimation mechanisms, namely the Schoute's, Bayesian, optimum, and ideal estimate $\hat{n} = n$. In all cases the optimum initial frame size is $r_0 = 1$.

Schoute's estimate is $\hat{n} = \text{round}(2.39c)$, where c is the number of slots collided in the same frame.

In the Bayesian estimate $\hat{n}$ is attained as the n that maximizes the "a posteriori" probability distribution of the backlog n, conditioned on all past history, starting from the "a priori" distribution of the population size N, Poisson in our case. The procedure is inspired to the work in [15].

In the optimum estimate the entire sequence $\{r_i\}$ of frame length is chosen in such a way as to maximize throughput taking into account all history. This is made by searching the tree of the strategies where nodes represent the slot outcomes. Since in the tree of the strategies some branches have infinite length (though with zero probability) we have searched until either: a leaf is reached, i.e., all terminals have been solved, or a node with a very small probability is reached. Here we have evaluated an upper and a lower bound for the remaining length. After averaging with the Poisson distribution, truncated at $N = 8$, we have found that the bounds practically coincide, providing the efficiency shown in the table.

Table II shows the maximum throughput of some strategies when frame restart is allowed. Under the Bayesian column we show the result of the strategy presented in the work of Floerkemeier [15]. In this case the "a posteriori" probability p_n is used to find the frame length r that maximizes the throughput of the next slot. This estimate provides slightly better results than setting r equal to the n that maximizes the "a posteriori" probability. If r does not match the remaining frame length a new frame is restarted with length r.

The Bayesian procedure is quite complex. However, we have observed that most of the gain of the Bayesian technique lies in avoiding the exploration of the last slot of the frame when a collision is certain. A simple mechanism capable to do that, and to provide a fairly good estimate with small groups, is the following, named Backlog Lower Bound (BLB):

$$\hat{n}_k = \max\{\hat{n}_{k-1} - s_k, 2c_k\}, \qquad k > 1,$$

and $\hat{n}_1 = 2$, being s_k and c_k respectively the number of successes and observed collisions in frame k up to that point. With BLB, n_k is evaluated before the last slot of the frame k and a new frame is started whenever we have $\hat{n}_k - s_k \geq 2$ and $c_k = 0$; otherwise, the last slot is observed, $\hat{n}_k$ is updated and a new frame is started. In both cases the length of the new frame is $r_{k+1} = \hat{n}_{k+1}$.

With frame restart the evaluation of the optimal strategy is much more complex and when our search is stopped the bounds are still a few decimal points apart. Therefore we have reported both the performance evaluated with these bounds.

IV. Partitioned Frame Slotted Aloha

Partitioned Frame Slotted Aloha uses a grouping procedure (Outer Protocol), and groups are identified using any DF-Aloha mechanism (Inner Protocol) described in the previous section, adjusting the group size in order to match the optimal size for the chosen Inner Protocol according to Table II. In the following, we explain the mechanism and prove that the asymptotical throughput is given by the Poisson throughput of the protocol adopted as Inner Protocol, 0.455 and 0.469 in the BLB and Bayesian cases respectively.

Let us assume for the moment that the population size N is known. Then the N tags can be subdivided into groups of average size γ in the following way. In the first round tags are solicited to respond with probability $p_0 = \gamma/N$. The number S_0 of tags that respond is binomially distributed with average $\gamma = p_0 N$, and with large N its distribution becomes Poisson. Therefore, we can use any protocol of the DF-Aloha family seen in the previous section, say inner protocol X, to solve the tags of first sub-group. Then a second round is started forcing the remaining $N_1 = N - S_0$ tags to respond with probability $p_1 = \gamma/N_1$. In general, at round i the remaining number of tags is

$$N_i = N - \sum_{j=0}^{i-1} S_j,$$

where the sum is zero for $i = 0$, and the response probability is

$$p_i = \frac{\gamma}{N_i}, \qquad i \geq 0.$$

The above procedure is repeated, and p_i increases as more tags are solved, until the last group of tags is forced to transmit with probability 1 and no further round is needed. The number of rounds V is a random variable that depends on the outcome S_i at each round and is such that

$$\sum_{i=0}^{V} S_i = N.$$

From the results of the previous section we see that the more convenient value for γ is close to one, therefore the optimum initial frame length for the inner protocol is always $r_0 = 1$.

Letting $D(n)$ denote the average number of slots needed to identify n tags, we can write a recursive relation in D as follows

$$D(n) = \sum_{k=0}^{n} [L(k,1) + D(n-k)] \operatorname{Bin}(n,k,p_n), \quad n \geq 2, \tag{2}$$

where $\operatorname{Bin}(n,k,p_n)$ is the binomial probability that k out of n tags respond with probability p_n, and $L(k,1)$ is the average number of slots needed by the inner protocol to solve k collisions. Equation (2) can be solved with respect to $D(n)$, which yields

$$D(n) = \frac{(1-p_n)^n + \sum_{k=1}^{n} [L(k,1) + D(n-k)] \operatorname{Bin}(n,k,p_n)}{1-(1-p_n)^n}, \tag{3}$$

for $n \geq 2$. Values $D(n)$ can be optimized in γ, providing $D^*(n)$. Relation (3) can be solved to provide $D^*(n)$ recursively starting from $D^*(0) = 0$ and $D^*(1) = 1$.

Table III reports the throughput and the optimum value γ_o for different values of n when the inner protocols are the Bayesian and the BLB mechanism of the previous section.

When $N \to \infty$, the binomial distribution in (2) becomes a Poisson distribution and the average length of the first round becomes $L_\gamma = \gamma/\eta$, being η the Poisson throughput of the inner protocol adopted. Since the average number γ of tags solved in the first round is finite, length $n-k$ also diverges with n and the argument can be repeated. Therefore, for large N, we have

$$D(N) = L_\gamma + L_\gamma + \ldots = (\gamma + \gamma + \ldots)/\eta = N/\eta,$$

and

$$\lim_{N \to \infty} = \frac{N}{D(N)} = \eta.$$

In practice, N is not known, and the size of the first sub-group can not be set to determine a given average γ. However, whichever the sizes of the first i sub-groups are, provided that they are not all zero, at the end of round i we know the number of tags $S = \sum_{j=0}^{i} s_j$ resolved up to that round, and this allows to get a first estimation $\hat{N}$ of N, that is subsequently refined in the following rounds, similarly to the procedure presented in [7]. These S tags appear as the result of a binomial experiment on the N tags, where the partition probability is given by

$$P = 1 - \prod_{j=0}^{i} (1 - p_j).$$

The estimation procedure is borrowed from [16] and is given by

$$\hat{N} = \frac{S}{P}. \tag{4}$$

This allows to estimate the remaining number of tags, n, to be identified as $\hat{n} = \hat{N} - S$, and to determine the probability p to provide γ as $p(\hat{n}) = \gamma/\hat{n}$. In practice, the average number of tags to be dealt with in round $i+1$ is

$$\gamma_n = p(\hat{n})n = \gamma \frac{n}{\hat{n}}. \tag{5}$$

During round $i+1$, k tags are drawn according to the binomial distribution $\operatorname{Bin}(n,k,p(\hat{n}))$. They are solved by the inner protocol in an average number of slots equal to $L(k,1)$. The average number of slots $D'(n,\gamma_n,S,P)$ needed to solve all the n tags unresolved at round i is therefore

$$D'(n,\gamma_n,S,P) = \sum_{k=0}^{n} [L(k,1) + D'(n-k,\gamma_{n-k},S',P')] \times \\ \times \operatorname{Bin}(n,k,p(\hat{n})), \tag{6}$$

for $n \geq 2$, where $S' = S + k$ and $P' = 1 - (1-P)(1-p(\hat{n}))$. Relation (6) can be resolved by recursive calls in a similar manner as done with (3).

In [16] it has been proved that $E[\hat{N}] = N$, $\operatorname{Var}[\hat{N}] = \frac{N}{P} - N$, and

$$\Pr\left(\left| \frac{\hat{N}}{N} - 1 \right| \geq \epsilon \right) \leq \frac{1-P}{\epsilon^2 NP}. \tag{7}$$

Equation (7) shows that, for any $P > 0$, for $N \to \infty$, $\hat{N}/N$ converges to 1 in probability. The same holds for intermediate values n.

Relation (5) shows that as $n \to \infty$, and $\hat{n}/n$ converges to 1 in probability, also γ_n/γ converges to 1 in probability. This shows that, after an initial phase in which the estimation converges, and if we set the proper value for γ, the algorithm solves the remaining tags with the efficiency η of the inner protocol X.

If the number of tags in the estimation phase, whose average is NP, is resolved in the worst case in a period of time T', with efficiency $\alpha = NP/T'$, then the overall solution time is $T = \frac{NP}{\alpha} + \frac{N(1-P)}{\eta}$, and the overall efficiency is

$$\frac{N}{T} = \frac{1}{\dfrac{P}{\alpha} + \dfrac{(1-P)}{\eta}} \simeq \eta \tag{8}$$

since, from (7), for very large values of N, P can be so small as to be negligible in (8).

For finite values of N the efficiency can be sensibly lower than η, depending on α and N itself. The overall performance is, in fact, determined by the value of the initial estimate $\hat{N}$ that determines the size of the first sub-group. If $\hat{N}$ is chosen too low the first sub-group can be very large with respect to N and the gain of the partitioning is lost. On the other side, if $\hat{N}$ is set too high the first sub-group is empty with high probability and no estimate by (4) can be drawn.

Therefore, we have modified the initial phase in which, starting from a unique initial estimate $\hat{N}_0$, suitable for any N and determined later on, the initial estimate $\hat{N}$ is set according to the following new rules. If the first slot is successful, then we set $\hat{N}_0 \to \hat{N}$ and the protocol proceeds as the basic PDFSA already described, adjusting the estimate and letting transmit a new sub-group of tags. If the first slot is empty, the estimate is reduced by half ($\hat{N}_0/2 \to \hat{N}_0$), and is further reduced by half at each consecutive empty slot until a non-empty slot is observed, in which case we set $\hat{N}_0 \to \hat{N}$ and the basic PDFSA protocol is adopted up to the end of the process. If the first slot is collided, the estimate is doubled

Table III
Performance of PDFSA with known N and the Bayesian and the BLB technique as inner protocols.

$N/D^*(N)$	$N=2$	$N=3$	$N=5$	$N=10$	$N=20$	$N=100$	$N=1000$
γ_o	1	1.11	1.15	1.17	1.18	1.1	1.1
Bayes	0.647	0.598	0.552	0.516	0.492	0.469	0.463
γ_o	1	1.08	1.14	1.17	1.18	1.19	1.19
BLB	0.632	0.582	0.537	0.502	0.483	0.463	0.459

Table IV
Performance of PDFSA with unknown N and the initial phase with the BLB technique as inner protocol, for different values of the initial estimate $\hat{N}$ and optimal γ.

$N/D^*(N)$	$N=1$	$N=2$	$N=3$	$N=5$	$N=10$	$N=20$	$N=100$	$N=1000$
$\hat{N}_0=1,\ \gamma=1.1$	1	0.428	0.378	0.372	0.381	0.405	0.439	0.455
$\hat{N}_0=2,\ \gamma=1.1$	0.5	0.541	0.434	0.402	0.396	0.411	0.442	0.455
$\hat{N}_0=4,\ \gamma=1$	0.333	0.450	0.4301	0.423	0.415	0.420	0.443	0.452
$\hat{N}_0=8,\ \gamma=1.3$	0.25	0.400	0.431	0.434	0.424	0.425	0.444	0.455

($\hat{2N_0} \to \hat{N}_0$), and is doubled at each consecutive collided slot until a non-collided slot is observed. If the non-collided slot is empty the estimate is halved. In either cases we set $\hat{N}_0 \to \hat{N}$ and the basic PDFSA protocol is adopted up to the end of the process.

Since the overhead of the estimation phase has greater impact with relatively small values of N, to reduce this impact we expect to assume low values for $\hat{N}_0$. If we assume, for example $\hat{N}_0 = 1$, the length of the initial phase, that is all composed by collided slots, may be conservatively estimated assuming that it lasts until the initial estimates reaches N, that is at $k-th$ slot, $k = 1, 2, \ldots$, of the initial phase, where $N \simeq 2^{k-1}$. Thus, for large N we have $k \simeq \log_2 N$, which shows that $\lim_{N\to\infty} k/N = 0$. Therefore the initial phase can only improve the performance of low values of N while has no impact asymptotically.

Table IV reports the efficiencies of PDFSA, with the initial estimation phase, for $\hat{N}_0 = 1, 2, 4, 8$ and γ chosen in such a way to maximize the minimum efficiency observed over N. The results are obtained by simulation. By comparing the BLB case of Table IV we see that the estimation has practically no penalty for high values of N such as $N = 1000$. The values more affected by the procedure are those around $N = 1$ and $N = 10$. This is common to procedures that depend on the setting of an initial parameter, to the point that efficiencies of these procedures below $N = 10$ are often not given. Ours maintains a very good efficiency for $N \geq 2$, and, if we are only interested to values $N \geq 3$, then the best choice is $\hat{N}_0 = 8$ and $\gamma = 1.3$. To our knowledge these are the best results ever observed in a pure DF-Aloha protocol and the second best in the whole field, where the best is the IECR in [7], that uses binary tree splitting.

V. Conclusions

In this paper we have discussed the issue of grouping in Dynamic Frame Aloha for RFID and have indicated how to set the optimal size of groups, based on results attained decades ago in random access systems. Furthermore, we have presented a novel protocol, Partitioned Dynamic Frame Slotted Aloha (PDFSA), based on grouping, that can provide an efficiency above 0.420 for any value of the population size N, reaching 0.455 asymptotically. Also, we have shown that adopting the best estimation mechanism the asymptotical efficiency rises to 0.469.

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