Markovian Model for Computation of Tag Loss Ratio in Dynamic RFID Systems

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Abstract

In Radio Frequency Identification (RFID) systems a reader device detects and identifies nearby electronic tags. Traditionally,the performance of RFID systems and their identification protocols has been analyzed for static configurations, that is, without considering incoming or outgoing tags, but just a fixed number of initially unidentified tags ,and also it has been measure in terms of throughput, average number of cycles or slots and average identification delay. However, many real scenarios cannot be consistently modeled in that way and also the metrics focused on "averages" do not answer key questions which we have to solve when we make a real RFID system planning. For instance, one of the most important issues to solve is to ensure the total, or at least a high percentage of identificactions in a RFID system. In this work we introduce a Markov model which allows us to study a dynamic RFID tag scenario, where a flow of tags (traffic) is considered. This model can be used to compute the Tag Loss Ratio, that is, the ratio of the outgoing unidentified tags to the incoming tags in the system, which is a critical metric in dynamic configurations. Besides, the analysis is carried out for two families of protocols used as medium access control in RFID: framed slotted Aloha and non-persistent CSMA.

1 Introduction

Radio Frequency Identification (RFID) systems are one of the enabling technologies for the ubiquitous computing paradigm [1]. Its foreseen application range spans from replacement of bar-code systems to location of containers in large vehicles. A wide range of RFID technologies have been in study to match such a broad scope of applications. All of them share a common architecture: a basic RFID cell which is composed of a reader device (*aka* master) and a (potentially large) set of RFID tags, which reply to the queries or enforce the commands from the interrogator (see Figure 1).

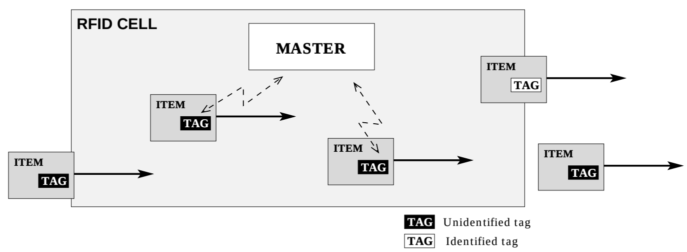


Figure 1 RFID cell with tag traffic

The system operates as follows: periodically the master transmits a *collection command* requesting the identification of tags in range. This command is answered only by tags not identified yet. When an identification round ends the master acknowledges all the correctly received identifications, making these tags quit from the rest of the identification process. This scheme is conceptually simple, but performance may be poor in case of collision:when multiple tags receive simultaneously a collection command (as in the example of Figure 1), reply messages may collide and cancel each other, preventing identifications. Therefore, this procedure is often complemented with Medium Access Control (MAC) mechanisms that avoid tag collisions and improve performance, for instance, a Framed Slotted Aloha (FSA) protocol, a Carrier Sense Multiple Access (CSMA) contention algorithm, or some more sophisticated selection procedure for the identification cycle duration [2].

The main objective of the master is to identify and communicate with the tags as quickly and *reliably* as possible, ensuring that all tags have been identified. As far as the authors know, such a problem has been studied for *static* scenarios, that is, a RFID cell with an initial population of unidentified tags is considered, and the goal is to analyze the time required for identifying the entire population, in terms of average number of cycles, slots, etc. This topic has already been addressed in several works [3, 4].However, such a static assumption is not realistic for a broad set of RFID applications. For example, consider a conveyor belt carrying industrial items to be identified, in such a system, there is a *flow of tags or input/output traffic*: while unidentified tags contend for identifying themselves, new items arrive and older ones leave the system (see Fig. 1). In these *dynamic* systems, the most important issue is to analyze the system *reliability*, which is the probability of reaching a percentage of successful identifications in a determined time when a poopulation of tags are in coverage or, in other workds the Tag Loss Ratio (henceforth, TLR), i.e., the ratio of the outgoing unidentified tags to the incoming tags in the RFID cell. So far, this problem has been studied by simulation [5].

In this paper we analytically address this problem and propose a Markov model for a dynamic RFID system, which allows us to compute the TLR,given a tag input traffic characterized by an arrival distribution. With this model we compute the TLR for both the FSA and CSMA medium access control approaches. To the best of the authors knowledge, this is the first approximation to the analysis of dynamic RFID systems.

The remainder of this paper is organized as follows. In Section 2 we briefly review the related work in the area. In Section 3 the system under study is thoroughly described, for both FSA and CSMA configurations. Then, in Section 4 we derive a markovian model of such system, and develop expressions for the Tag Loss Ratio. Section 5 provides a set of scenarios where the use of the former expressions is exemplified. Finally, section 6 concludes and outlines possible future works.

2 Related Work

In general, the tag identification problem deals with identifying multiple objects with (i) minimal delay and power consumption, (ii) reliability, (iii) line-of-sight independence, and (iv) scalability.

In this paper we analyze two families of MAC protocols for RFID: FSA and CSMA. FSA is the more extended solution for both passive [2, 3] and active tags [6, 7]. However, we also consider CSMA since in [4] it is shown that the use of non-persistent CSMA as anti-collision mechanism for active RFID tags improves performance and scalability. In that paper we supported this solution by studying analytically the performance of quasi-optimal non-persistent CSMA as an anti-collision mechanism in a static scenario. In this paper we provide a model for the dynamic case.

Both CSMA and framed slotted ALOHA have been extensively studied [8, 9], but as classical MAC protocols, focusing on the channel utilization and access delay. In RFID, on the contrary, the appropriate performance metrics are the identification delay and TLR. Although the method proposed by Wieselthier [9] can be adapted to compute the TLR, it only holds for FSA whereas our model is not specifically focused on FSA, and can be extended to other MAC protocols.

On the contrary, few analysis of RFID protocols performance can be found in the literature. Splitting algorithms are addressed in [10]. Since this kind of protocols is deterministic, performance is evaluated in terms of the average number of time slots needed to complete the process. Vogt [3] analyzes the identification process of framed slotted ALOHA as a Markov chain but only the static case is considered. In this paper we use a Markov model, but, unlike Vogt, we do consider tag arrivals and departures.

3 System Operation

In this work we consider a RFID scenario similar to the one depicted in Figure 1. We consider an incoming flow of tags entering the coverage area of a master (RFID cell), moving at the same speed (e.g., modelling a conveyor belt). Therefore, all tags stay in the coverage area of the reader during the same time. Every tag not identified during that time is considered as lost. As stated in the introduction, a tag is identified when its identification number (ID) is correctly received and acknowledged by the reader. Once acknowledged, a tag withdraws from the identification process, that is, does not try to send its ID again. The master periodically requests IDs sending a *collection* packet. Tags try to send its ID after receiving a query packet. The actual operation depends on the protocol in use, as we will discuss next.

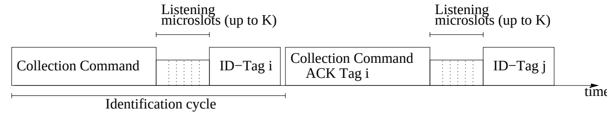


Figure 2 Anti-collision procedure with CSMA

3.1 Carrier Sense Multiple Access

The operation of the identification protocol when using CSMA is as follows: after receiving a collection command from the master all tags listen to the channel for k *micro-slots*, where k is randomly chosen in the interval $[1, \ldots, K]$ (K denotes the maximum number of micro-slots, and it is a configuration parameter of the system). If the channel remains idle after k micro-slots, the tag sends its ID. Otherwise, it withdraws until the next collection command (next cycle). Notice that collision is possible if two or more tags choose the same k. If there is no collision, the master sends an ACK-Collection command, which indicates the tag identified and asks for more IDs. The remaining nodes start the process again. Fig. 2 illustrates this mechanism. Note that in this case, in a given collection cycle, there can only be zero or one identifications.

Both ISO 18000-7 and EPC "Gen 2" [6, 7] define a similar anti-collision procedure that we generically call "Framed slotted ALOHA" (FSA). In both cases, a population of tags start the identification process after receiving a collection command from the master. At this moment, tags randomly select a slot with a uniform distribution and transmit their ID in the selected slot. Let us denote the number of possible slots to choose as *frame length*, K. If two or more tags select the same slot, a collision occurs. For each slot with a single reply, the interrogator sends an ACK packet which enforces the tag to sleep, preventing it from participating again in the identification process. Thus, the acknowledged tags (already identified) withdraw from contention in the following rounds. Fig. 3 illustrates this process. We refer to a collection command plus the K slots as an *identification cycle*. It should be noted that unlike CSMA, with FSA an identification cycle involves several slots and more than one tag can be identified.

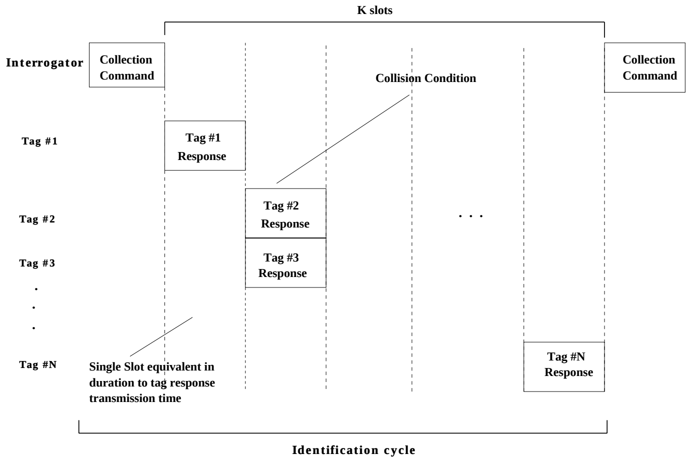


Figure 3 Anti-collision procedure of ISO 18000-7, reproduced from [6]

3.2 Framed Slotted ALOHA

Besides, comparing CSMA and FSA identification times is not straightforward since the identification cycles have a different nature in both systems. Typically, several CSMA-cycles can be contained in a single FSA-cycle, since the micro-slots length is much smaller than a slot in FSA. Furthermore, the cycle length in CSMA is variable, while it is fixed in FSA. Therefore a fair comparison between both access methods require a careful selection of parameters, and operate with time units instead of "cycles". Such issue is beyond the scope of this paper since here we focus on the model, interested readers may consult [4].

4 System Model and Analysis

Thereafter, the following notation and conventions are used:

- Probabilities are denoted as $Pr\{\text{Event}\}$.
- Random variables are denoted as $\boldsymbol{v}$ and stochastic processes as $\boldsymbol{X}$.
- A row vector is denoted as $\vec{V}$.
- The i-th component of a vector is denoted $(\vec{V})_i$.
- $\sigma(\vec{V})$, the sum of the values of the components of a vector $\vec{V}$, i.e. $\sigma(\vec{V}) = \sum_{k=1}^{dim(\vec{V})} (\vec{V})_k$, being $dim(\vec{V})$ the dimension of vector $\vec{V}$.

Let us define an *identification cycle*, as the interval of time of duration T_c between consecutive collection requests (independently of the underlying medium access mechanism). Zero, one or more tags may be identified during each identification cycle. Additionally, let us denote T as the time a tag remains in the RFID cell. For simplification, let us assume that T is a positive integer multiple of T_c, that is, the tags stay in the RFID cell for a given amount of collection cycles. Let us denote N as the number of cycles in the coverage area plus one. Therefore, T can be expressed as $T = (N-1)T_c$. Once a tag has entered the coverage area, it should be identified in the following $N-1$ identification cycles. Otherwise (if it reaches the cycle N), it is lost. Indeed, this assumption allows us to use the expression "a tag in the i-th cycle", which refers to a tag that remains in the system for a time in the interval $[(i-1)T_c, iT_c)$, for $i = 1, \ldots, N$. To avoid confusions between the absolute number of cycles elapsed since system startup and the relative identification cycle of one tag, we will explicitly use the word id-cycle henceforth to denote the relative identification cycle of one tag in the system.

In addition, note that incoming tags entering the system *after* a collection command do not participate in the current identification cycle since they do not receive the collection packet. Therefore, we can model incoming traffic in our system as a discrete arrival process. Let us assume that the arrival process for the i-th cycle is modeled by a discrete stationary stochastic process $\boldsymbol{A}(i)$. Therefore, the number of arrivals does not depend on the cycle considered (we can denote it just $\boldsymbol{A}$). Besides, assume that $\boldsymbol{A} \leq H$, for some $H \in \mathbb{N}$, i.e. in a given time-slot the maximum number of new tags is H (which may be arbitrarily high, but finite). Finally, let us denote $a(h) = Pr\{\text{h arrivals in } T_c\}$, for each $h = 0, \ldots, H$, as the probability distribution of the arrival process $\boldsymbol{A}$.

4.1 Discrete dynamics

The former assumptions allow us to express the dynamics of our system as a discrete model, evolving cycle by cycle, such that,

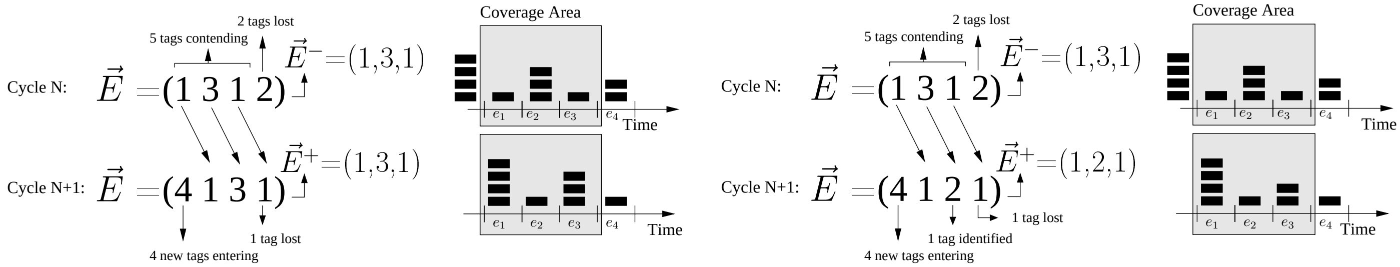
- Each tag belongs to one *id-cycle* in the set $[1, \ldots, N]$
- After a cycle, identified tags withdraw from the identifation process, and we consider that they leave the system.
- After a cycle, each tag unidentified and previously in the j-th *id-cycle* moves to the $(j+1)$-th *id-cycle*.
- If a tag enters *id-cycle* N, it is considered out of the range of the reader, and, therefore, lost.
- At the beginning of each cycle, $\boldsymbol{A}$ new tags are assigned to *id-cycle* 1.

For any arbitrary cycle, the evolution of the system to the next cycle only depends on the current state. Thus, a Markov model can be used to study the behavior of the RFID system. Next section describes this model.

4.2 Markovian model

Based on previous considerations, our system can be modeled by a homogeneous discrete Markov process $\boldsymbol{X}_c$, whose state space is described by a vector $\vec{E} = \{e_1, \ldots, e_N\}$, where each $e_j \in (0 \ldots H)$, representing *the number of unidentified tags in the j-th* id-cycle. Figure 4 illustrates our model. It describes the state of the system for two consecutive cycles, showing tags entering and leaving the system, in both identification and no identification scenarios.

Therefore, $(\vec{E})_j$ is the number of tags which are going to start their j-th identification cycle in coverage. $(\vec{E})_1$ component also represents the number of tag arrivals during the previous identification cycle (which do not contend since they have not received a collection packet yet). Finally, component $(\vec{E})_N$ indicates the number of tags lost at the



(a) Case 1: No identification (b) Case 2: Identification

Figure 4 Representation of a state transition

```
function E_i=itovec(i,H,N)
   i=i-1; j=N;
   while j>0 {
     e_j=i(H+1)^{j-1};
     i=i-e_j(H+1)^{-1};
     j=j-1
   }
```

Figure 5 Algorithm to build the state space

end of the identification cycle, since tags leave coverage area after $N-1$ cycles.

In addition, let us define the mapping Ψ as a correspondence between the state vector and an enumeration of the possible number of states:

$$\begin{aligned} \Psi : & [0,\dots,H] \times^{(N)} \times [0,\dots,H] \rightarrow [1,\dots,(H+1)^N] \\ & \vec{E} = \{e_1, e_2, \dots, e_N\} \rightarrow \Psi(\vec{E}) = 1 + \sum_{j=1}^{N} e_j H^{j-1} \end{aligned} \quad (1)$$

Obviously, Ψ is an injective mapping, and, since both sets have the same cardinality, it is a bijection mapping, and so there exists an inverse mapping Ψ^{-1}. This property allows us to define the i-th state in our model as the state whose associated vector is given by Ψ^{-1}. Let us denote $\vec{E_i}$ as the vector associated to the i-th state, i.e., $\vec{E_i} = \Psi^{-1}(i)$. Fig. 5 provides an algorithm to compute the vector associated to a given state i.

Now, the goal is to describe the transition probability matrix P for the model, from every state i to another state j. Indeed, P depends on the underlying anti-collision protocol used. Once found, the stationary state probabilities can be computed as $\vec{\pi} = \vec{\pi}P$, where the vector $\vec{\pi}$ denotes the stationary probability distribution of the state space, $\vec{\pi} = \{Pr\{\vec{E_1}\}, \dots, Pr\{\vec{E}_{(H+1)^N}\}\}$.

As stated in the introduction, we are mainly interested in the *Tag Loss Ratio*, TLR, i.e. the ratio of the outgoing unidentified tags to the incoming tags in the system. Let us define λ_j as the average incoming traffic of unidentified tags in the j-th *id-cycle*, for $j = 1, \dots, N$. So,

$$\lambda_j = \sum_{i=1}^{(H+1)^N} (\vec{E_i})_j (\vec{\pi})_i \quad (2)$$

Obviously, λ_1 is the average incoming traffic in the system (therefore, $\lambda_1 = \overline{\boldsymbol{A}}$), and λ_N is the average outgoing traffic of unidentified tags out of the system. That is,

$$TLR = \frac{\lambda_N}{\lambda_1} = \frac{\sum_{i=1}^{(H+1)^N} (\vec{E_i})_N (\vec{\pi})_i}{\overline{\boldsymbol{A}}} \quad (3)$$

In the following section we derive the probability transition matrix (P) and the associated TLR for the two families of identification protocols under study: CSMA and Frame Slotted ALOHA.

4.3 CSMA

In this case, let us denote $s(\boldsymbol{f}, n)$ as the probability of success (one tag identified in the collection cycle) when n tags select a contention micro-slot using probability distribution $\boldsymbol{f}$. Let us denote f_r as the probability that each contender independently picks micro-slot r, from $r = 1, \dots, K$, i.e. $f_r = Pr\{\boldsymbol{f}{=}r\}$. Probability $s(\boldsymbol{f}, n)$ is computed in [11], and its expression is reproduced in equation (4).

$$s(\boldsymbol{f}, n) = n \sum_{z=1}^{K-1} f_z (1 - \sum_{r=1}^{z} f_r)^{(n-1)} \quad (4)$$

Besides, let us denote $p_{ij}{=}Pr\{\boldsymbol{X}_c = \vec{E_j} | \boldsymbol{X}_{c-1} = \vec{E_i}\}$, i.e. the transition probability from state i to state j.

To help building the transition probability matrix P let us define the auxiliary vectors $\vec{E}_i^-$ and $\vec{E}_i^+$ as:

$$\begin{aligned} \vec{E}_i^- &= \{(\vec{E_i})_1, \dots, (\vec{E_i})_{N-1}\}, \\ \vec{E}_i^+ &= \{(\vec{E_i})_2, \dots, (\vec{E_i})_N\} \end{aligned} \quad (5)$$

Respectively, a vector without either the last or the first component.

Finally, let us define $\eta(i,j)$ as the number of identified tags in a transition from a state i to a state j (see Figure 4). Notice that if $(\vec{E_i})_k < (\vec{E_j})_{k+1}$ for some $k = 1, \dots, N-1$ this transition is impossible (new tags can not appear in *id-cycles* different than *id-cycle* 1). Let us denote impossible transitions with $\eta(i,j)$ value equal to -1. Then, $\eta(i,j)$ is provided by equation (6).

$$\eta(i,j) = \begin{cases} \sigma(\vec{E}_i^- - \vec{E}_j^+), \text{ if } (E_i)_k \geq (E_j)_{k+1} \\ \text{ for } k = 1, \ldots, N-1 \\ -1, \text{ otherwise} \end{cases} \tag{6}$$
$$\text{for each } i, j \in [1, \ldots, (N+1)^H]$$

Then, we can build the transition matrix P for the Markov process $\boldsymbol{X}_c$ taking into consideration that:

- As stated in section 3, using CSMA only one identification is possible in each cycle.
- In each cycle, the number of contending tags is given by $\sigma(\vec{E}_i^-)$, for a given state i.
- $\eta(i,j) = 0$ for the no identification case (represented in Figure 4.(a)). In this case, there is not success in the collection cycle.
- $\eta(i,j) = 1$ when there is success, since only 1 tag can be identified in each CSMA identification cycle (see Figure 4.(b)). In this case, the probability of success is uniformly distributed between all the contenders ($\sigma(\vec{E}_i^-)$). Therefore, the probability that identification occurs in the *id-cycle* k ($\gamma_i(k)$) considering the initial state i, is given by equation (7).

  $$\gamma_i(k) = \frac{(\vec{E}_i)_k}{\sigma(\vec{E}_i^-)} \tag{7}$$
  $$\text{for each } k = 1, \ldots, N-1$$

  In fact, if the final state is j, the *id-cycle* which the identified tag belongs to is given by ($iden(i,j)$):

  $$iden(i,j) = k, \text{ if } (\vec{E}_i^- - \vec{E}_j^+)_k = 1 \tag{8}$$

  Notice that since $\eta(i,j) = 1$ this is an injective function.
- In the two previous cases the probability of the arrival of new tags must be taken into account, which corresponds to $a((\vec{E}_j)_1)$. Since the arrival process in independent from the identification process, the joint probability is directly computed.
- Otherwise, the transition is impossible, and thus it has a null probability.

Summing up, equation (9) represents the transition probability P for the CSMA anti-collision protocol,

$$p_{ij} = \begin{cases} a((\vec{E}_j)_1)[1 - s(\boldsymbol{f}, \sigma(\vec{E}_i^-))] & , \text{ if } \eta(i,j) = 0 \\ a((\vec{E}_j)_1)[s(\boldsymbol{f}, \sigma(\vec{E}_i^-))]\gamma(iden(i,j)) & , \text{ if } \eta(i,j) = 1 \\ 0 & , \text{ otherwise} \end{cases} \tag{9}$$

4.4 Framed Slotted Aloha

For a given collection cycle, let us denote K as the number of available contention slots (see Section 3) and M the number of contending tags. In this case, let us define the random variable $\boldsymbol{s}(K,M)$ that indicates the number of contention slots being filled with exactly with 1 tag, for a given number of slots and competing tags. The mass probability function of $\boldsymbol{s}(K,M)$ has been computed in [3], and is reproduced in equation (10).

$$Pr\{\boldsymbol{s}(K,M) = k\} = \frac{\binom{K}{k} \prod_{i=0}^{k-1}(M-i) G(K-k, M-k)}{K^M} \tag{10}$$

Besides, the auxiliary function G is defined as follows,

$$G(a,l) = a^l + \sum_{i=1}^{l} \left\{ (-1)^i \prod_{j=0}^{i-1} \{(l-j)(a-j)\} (a-i)^{l-i} \frac{1}{i!} \right\} \tag{11}$$

For simplicity, henceforth let us denote $Pr\{\boldsymbol{s}(K,M) = k\}$ as $s_k(K,M)$.

As stated in section 3, using FSA, up to K tags may be identified in a single collection cycle. Therefore, possible cases range from $\eta(i,j) = 0$ to $\eta(i,j) = K$. The probability of $\eta(i,j)$ successful identifications is again uniformly distributed between all the contenders. Thus, given a transition from state i to state j, we take into account the probability of all the possible ways of getting $\eta(i,j)$ with equation (12).

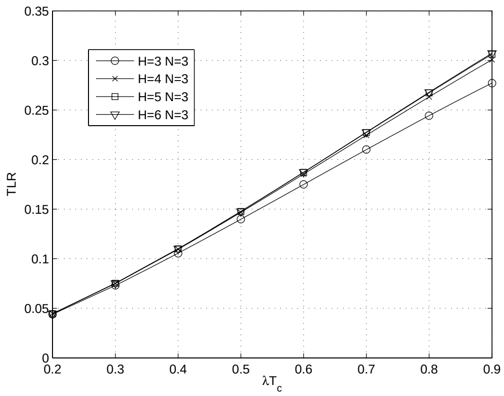
$$\nu(i,j) = \frac{\prod_{k=1}^{N-1} \binom{(\vec{E}_i^-)_k}{(\vec{E}_i^-)_k - (\vec{E}_j^+)_k}}{\binom{\sigma(\vec{E}_i^-)}{\eta(i,j)}} \tag{12}$$

From equation (10) and the previous definitions, the transition matrix P can be computed as shown in equation (13).

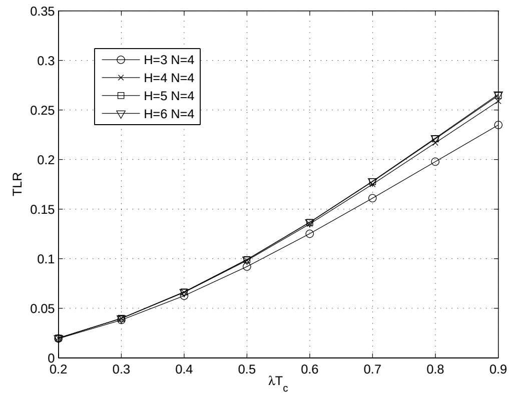
$$p_{ij} = \begin{cases} a((\vec{E}_j)_1) s_0(K, \sigma(\vec{E}_i^-)) & , \text{ if } \eta(i,j) = 0 \\ a((\vec{E}_j)_1) \nu(i,j) s_{\eta(i,j)}(K, \sigma(\vec{E}_i^-)) & , \text{ if } \eta(i,j) \in [1..K] \\ 0 & , \text{ otherwise} \end{cases} \tag{13}$$

5 Examples and results

We have computed TLR for different values of H and N and for both CSMA and FSA. For CSMA we have used the Sift approximation to the optimal distribution for $\boldsymbol{f}$ derived in [11]. As shown in [4] this distribution performs and scales better than FSA in the static scenario. We have used $K = 8$ contention microslots. For FSA we have selected $K = 8$ slots. In both cases, for the arrival process $\boldsymbol{A}$ we have selected a truncated Poisson distribution, with parameter λT_c:

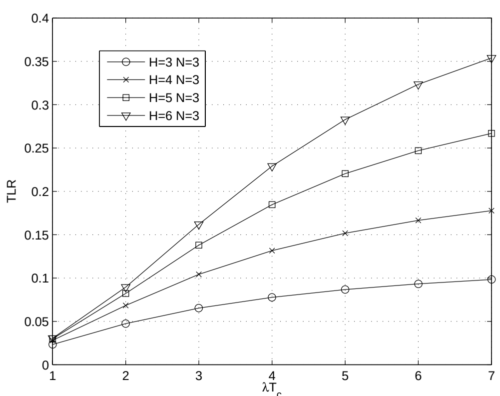


(a) N=3 and H=3 to H=6

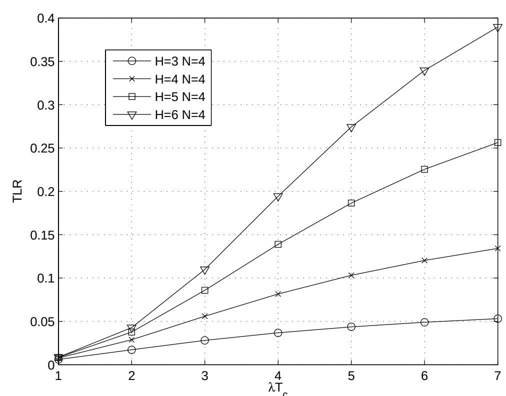


(b) N=4 and H=3 to H=6

Figure 6 TLR results for CSMA with Sift distribution (parameter M=32) with 8 contention microslots and Poisson arrivals



(a) N=3 and H=3 to H=6



(b) N=4 and H=3 to H=6

Figure 7 TLR results for FSA with 8 slots and Poisson arrivals

$$a(h) = \frac{(\lambda T_c)^h}{h! \sum_{i=0}^{H} \frac{(\lambda T_c)^i}{i!}}, h = 0 \dots H \quad (14)$$

However, as discussed in Sec. 3.2, CSMA identification cycles are different than FSA ones. One tag at most can be identified in a CSMA identification cycle, whereas up to 8 tags might be identified in a FSA one. Thus, to keep incoming traffic roughly comparable, λT_c range spans from 0.2 to 0.9 tags in CSMA whereas for FSA it spans from 1 to 7.

The results are shown in Fig. 6 and 7. They show that, keeping fixed N, TLR increases as maximum number of arrivals H increases, as expected. In addition, keeping fixed H, TLR decreases as the maximum number of cycles in coverage N increases, also as expected. The fact that for a given H, TLR is higher when N is higher is because there are more tags contending simultaneously. For example, for $H = 6$ and $N = 3$ there might be 12 tags contending at most whereas for $H = 6$ and $N = 4$ there might be up to 18 tags. It should be highlighted how CSMA handles better than FSA an increase in the number of new arrivals.

6 Conclusions

In this paper we have shown a Markov model for the analysis of dynamic RFID scenarios, that is, where an arbitrary number of tags flows through the coverage area of the reader. To the best of our knowledge this is the first model proposed for such systems. This model has been used to derive the *Tag Loss Ratio*, TLR, which is the metric of interest for RFID systems, where the main goal is to *reliably* identify all the tagged items. Besides, the TLR has been computed for both FSA and CSMA.

Possible applications of this model are:

- Since it provides an exact solution for the TLR, it can be used to validate RFID simulators for more complex/realistic systems.
- It can be used at design stage to evaluate the influence of different protocol parameters, such as the number of slots, in the system performance for several MAC protocols.

We leave the details on efficient implementation of the model with optimized programming libraries as future work. We are also working on new analytical models with a reduction in the number of states. Finally, we intend to apply these models and results in the design of optimized MAC protocols for RFID.

7 Acknowledgements

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