Chapter 3

An RFID Anti-Collision Algorithm Assisted by Multi-Packet Reception and Retransmission Diversity

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Additional information is available at the end of the chapter

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1. Introduction

1.1. RFID technology and previous works

RFID (Radio Frequency Identification) is a technology that uses radio frequency signals for purposes of identification and tracking of objects, humans or animals. In passive RFID systems, where tags reuse the energy radiated by the reader, coordination capabilities can be considerably limited [29]. This issue leads to conflicts or collisions between the transmissions of the different elements of an RFID network, i.e., readers an tags. An efficient medium access control layer (MAC) is thus crucial to the correct operation of RFID [3].

Two types of RFID MAC collision can be identified: tag and reader collision. A tag collision arises when several tags simultaneously respond to a given reader request, thus causing the loss of all the transmitted information. To address this issue, tag anti-collision schemes such as ALOHA and binary tree algorithms are commonly employed [3, 31]. Improvements on these solutions have been further proposed by using tag estimation methodologies [14], and modified frame structures [3, 30], among many other approaches in the literature. Two types of reader collision can also be identified: multiple-reader-to-tag collision and reader-to-reader collision [2]. To address these two issues, reader anti-collision algorithms based on scheduling or coverage control have been proposed. Typical scheduling schemes are frequency division multiple access (FDMA) [7] or listen-before-talk (LBT) [8]. Advanced schemes such as Colorwave in [28] and Pulse in [2] implement inter-reader control mechanisms to assist in the collision resolution process. Other approaches such as HiQ in [11] use an analysis of collision patterns over consecutive time-slots to improve scheduling policies. Regarding coverage-based algorithms, two types of scheme can be commonly found: those that reduce the overlapping coverage area between readers (e.g., [12]), and those that monitor interference to adapt power levels accordingly (e.g., [4]).

1.2. Open issues and chapter objectives

Despite recent advances in RFID MAC layer design, several issues remain open today. Current RFID algorithms are designed under simplistic assumptions such as the collision-model. In such a collision-model, collisions are regarded as the loss of all the transmitted information. On the contrary, collision-free transmissions are always assumed to be correctly received. These assumptions are, however, highly inaccurate, particularly for wireless settings with rapidly changing channel conditions and assisted by modern signal processing tools. In wireless networks, packet transmissions can be lost due to random fading phenomena and not only due to collisions. On the other hand, a collision with multiple concurrent transmissions can be resolved by means of multiple antenna receivers. Therefore, a new approach for a more accurate design and modeling of random access protocols in modern wireless networks is required. In the literature of conventional random access protocols, considerable advances in these aspects have been recently made using the concept of cross-layer design [18–26]. The objective of this chapter is to use two of these recent cross-layer solutions and modeling approaches to improve the performance of RFID. In particular, we focus on those solutions that make use of signal processing tools that exploit diversity in the space (multi-packet reception) and time domains (retransmission diversity).

1.3. MAC-PHY cross-layer design: Multi-packet reception and retransmission diversity

Multi-packet reception is a concept that has revolutionized the design paradigm of random access protocols. Conventionally, collisions were always considered as the loss of all the transmitted information. However, modern multiuser detection and source separation tools allow for the simultaneous decoding of concurrent transmissions. Design of random access protocols with multi-packet reception has been addressed in [9] using a symmetrical and infinite user population model, and in [16] using an asymmetrical and finite user population model. A novel multi-packet reception scheme that exploits the time domain in order to achieve diversity has been proposed in [26], and it has been called network diversity multiple access (NDMA). In NDMA, a virtual MIMO (multiple-input multiple-output) system is induced by requesting as many retransmissions as needed to recover the contending packets using source separation. A hybrid algorithm with multi-packet reception and retransmission diversity has been proposed in [21].

1.4. Chapter contributions

This chapter aims to use the concepts of multi-packet reception and retransmission diversity in the MAC layer design of passive RFID systems. To investigate these two cross-layer random access algorithms in the context of RFID, a novel framework which includes PHY (physical) and MAC (medium access control) layer parameters of RFID is here employed. The framework consists of the co-modeling of both the down-link (reader-to-tag) and up-link (tag-to-reader) signal-to-interference-plus-noise ratio (SINR) experienced in a multi-tag and multi-reader environment. This framework was first proposed in our previous work in [22], and it has been modified here to be used in the context of multi-packet reception and retransmission diversity. Based on this updated framework, stochastic models for tag activation/detection processes (considering multi-packet reception and retransmission diversity) are then proposed. The proposed approach also allows for a novel joint design of reader and tag anti-collision schemes. Conventionally, these two algorithms were designed independently from each other. However, readers and tags operate in the same frequency band. Therefore, contention between their transmissions can potentially arise. Furthermore, reader anti-collision policies directly influence tag activation, and thus also the way in which tags collide when responding to readers' requests. Therefore, a complete model of RFID MAC layer should consider both processes together rather than independently. The proposed framework fills this gap by simultaneously modeling tag activation and the corresponding tag responses to readers, while also considering multi-packet reception and retransmission diversity at the reader side.

To complement the framework for MAC/PHY cross-layer design, a Markov model is also presented, which allows for capacity and stability evaluation of asymmetrical RFID systems. The approach consists of defining the states (i.e., the set of active tags/readers) that describe the network at any given time, and then map them into a one-dimensional Markov model that can be solved by standard techniques such as eigenvalue analysis. The results show that the proposed algorithms as well as the joint cross-layer approach and the Markov model provide considerable benefits in terms of capacity and stability over conventional solutions.

1.5. Organization

The organization of this chapter is as follows. Section 2 describes the framework for cross-layer design, and gives details of the operation of the protocol with multi-packet reception and retransmission diversity. Section 3 describes the proposed metrics and the Markov model. Section 4 addresses the optimization of the system and displays the results using different scenarios. Finally, Section 5 presents the conclusions of the chapter.

2. System model and cross-layer framework

Consider the slotted RFID network depicted in Fig. 1 with a set $\mathcal{R}$ of K readers $\mathcal{R} = \{1, \ldots K\}$ and a set $\mathcal{T}$ of J tags $\mathcal{T} = \{1, \ldots, J\}$. Each reader is provided with M antennas that will be used to recover, using source separation, the simultaneous transmissions of several tags. Two main processes can be distinguished in the RFID network in Fig. 1: Tag activation by the transmission of readers, also called the down-link transmission; and the backscattering response towards readers by previously activated tags, also called up-link transmission. In the down-link, the transmit power of reader k will be denoted by $P_{r,k}$ while its probability of transmission will be denoted by $p_{r,k}$. All the antennas will be assumed to transmit the same signal in the down-link. The subset of active readers at any given time will be denoted by $\mathcal{R}_t$. Tags are activated when the signal-to-interference-plus-noise ratio (SINR) given a reader transmission is above an activation threshold. The set of activated tags will be denoted by $\mathcal{T}_P$. In the up-link, the active tags proceed to transmit a backscatter signal using a randomized transmission scheme. The subset of tags that transmit a signal once they have been activated will be given by $\mathcal{T}_t$, where each tag j will transmit with a power level denoted by $P_{t,j}$. Details of the down- and up-link models are given in the following subsections.

2.1. Tag activation process: Down-link model

Consider that the instantaneous channel between reader k and tag j is given by the column vector $\mathbf{h}_{k,j}$ with dimensions $M \times 1$, the channel experienced between reader k and reader m is given by the matrix $\mathbf{G}_{k,m}$ with dimensions $M \times M$, and the channel experienced between tag i and tag j is given by the scalar value $u_{i,j}$. The SINR experienced by tag j due to a transmission of reader k is denoted by $\gamma_{k,j}$, and it can be mathematically expressed as follows:

$$\gamma_{k,j} = \frac{P_{r,k}\mathbf{h}_{k,j}^{H}\mathbf{h}_{k,j}}{I_{r_{k,j}} + I_{t_j} + \sigma_{v,j}^{2}}, \qquad k \in \mathcal{R}_t, \tag{1}$$

where $I_{r_{k,j}} = \sum_{m \in \mathcal{R}_t, m \neq k} P_{r,m}\mathbf{h}_{m,j}^{H}\mathbf{h}_{m,j}$ is the interference created by other active readers, $I_{t_j} = \sum_{i \in \mathcal{T}_t, i \neq j} P_{t,i}(|u_{j,i}|^2)$ is the interference created by other tags, $(\cdot)^H$ is the hermitian transpose operator, and $\sigma_{v,j}^{2}$ is the noise. If the SINR experienced by tag j is above the tag sensitivity threshold $\widetilde{\gamma}_j$, then the tag becomes activated. The probability of tag j, which was previously inactivated, to become activated will be given by

$$\Pr\{j \in \mathcal{T}_P\} = \Pr\{\max_{k} \gamma_{k,j} > \widetilde{\gamma}_j\}. \tag{2}$$

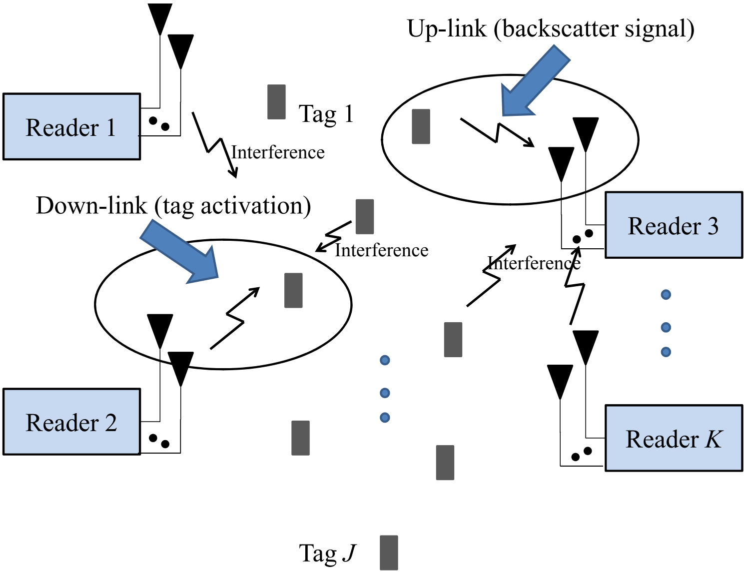

Figure 1. Multi-tag and Multi-reader deployment scenario.

2.2. Backscattering process: Up-link model

Once a tag j has been activated by the transmission of a given reader, it then starts a random transmission process to prevent collisions with other active tags using a Bernoulli process with parameter $p_{t,j}$, which is also the transmission probability. The backscattering factor β_j is the fraction of the received power reused by the tag to reply to the reader. Therefore, the transmit power of tag j can be calculated as $P_{t,j} = \beta_j P_{r,k} |h_{k_{opt},j}|^2$, where $k_{opt} = \arg\max_k \gamma_{k,j}$ denotes the reader that has previously activated the tag. At the reader side, source separation tools for multi-packet reception and retransmission diversity will be used. The proposed protocol consists of ensuring that the number of diversity sources is equal or larger than the number of contending tags so that the source separation technique is successful. For example, if 4 tags collide at a particular time-slot (see Fig. 2) and the reader is provided with only 2 antennas, then the system will request a retransmission from the contending tags in the following time slot. The reader will store all the signals collected during these 2 time-slots and will create a virtual MIMO system from which the signals of the contending tags can be estimated using multiuser detection. The array of stacked signals received at reader k across all r sources of diversity[1] is given by:

$$\mathbf{Y}_{r,k} = \mathbf{HS} + \mathbf{I}_{r,k} + \mathbf{E}_{r,k} + \mathbf{V}_{r,k} \tag{3}$$

where $\mathbf{H}$ is the stacked version of all the channels of the contending tags, $\mathbf{S}$ is the stacked version of all the signals of the contending tags, $\mathbf{I}_{r,k}$ is the collected interference created by other active readers, $\mathbf{E}_{r,k}$ is the collected leaked signal power from the transmission chain, and $\mathbf{V}_{r,k}$ is the noise term. At the reader side, a multiuser receiver such as zero forcing (ZF) or minimum mean square error (MMSE) can be implemented. For example, the zero forcing receiver can be described as follows:

$$\widehat{\mathbf{S}} = \widehat{\mathbf{H}}^{-1} \mathbf{Y}_{r,k}, \tag{4}$$

where $\widehat{\mathbf{S}}$ is the array of estimated signals of the contending tags, and $\widehat{\mathbf{H}}$ is the estimated channel of the contending tags. Since the resolution of a collision may take place over a random number of time slots due to the retransmission diversity scheme, then we will denote this collision resolution period as an *epoch-slot* with a length denoted by the random variable l_{ep}.

For simplicity, it will be assumed that the performance of the multiuser receiver is described by the ability to correctly detect the presence of all the contending tags. This assumption has been used in the analysis of conventional NDMA protocols in [26]. In this assumption any detection error yields the loss of all the contending packets. Thus, it is possible to propose the detection SINR of tag j at reader k, denoted by $\widehat{\gamma}_{j,k}$, as follows:

$$\widehat{\gamma}_{j,k} = \frac{P_{t,j} \mathbf{h}_{k,j}^H \mathbf{h}_{k,j}}{\widehat{I}_{r,k} + P_{r,k}\eta_k + \widehat{\sigma}_{v,k}^2}, \qquad j \in \mathcal{T}_t \tag{5}$$

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[1] the number of diversity sources is the total number of combinations of antenna elements and retransmissions

where $\widehat{I}_{r,k} = \sum_{m \neq k} \mathrm{tr}(\mathbf{G}_{k,m}^{H}\mathbf{G}_{k,m})$ is the interference created by other active readers, $\mathrm{tr}(\cdot)$ is the trace operator, η_k is the power ratio leaked from the down-link chain, and $\widehat{\sigma}_{v,k}^{2}$ is the noise. Note that tag-to-tag interference is not considered as an independent orthogonal training signal for each tag is used in each transmission for purposes of tag detection and channel estimation, which is also used in the original NDMA protocol in [26]. Thus, tag j can be detected by reader k if the received SINR is above a threshold denoted by $\check{\gamma}_k$. The set of detected tags by reader k will be denoted by $\mathcal{T}_{D,k}$, thus the probability of tag j being in $\mathcal{T}_{D,k}$ will be given by

$$\Pr\{j \in \mathcal{T}_{D,k}\} = \Pr\{\widehat{\gamma}_{j,k} > \check{\gamma}_k\}. \tag{6}$$

The set of correctly detected tags across all the readers will be simply given by $\mathcal{T}_D$, where $\mathcal{T}_D = \cup_k \mathcal{T}_{D,k}$. Since this detection process is prone to errors, we will use in this paper the same assumption used in the original paper for NDMA in [26] where tags are only correctly received at the reader side if all the contending tags are correctly detected and none of the remaining silent tags is incorrectly detected as active (i.e., false alarm). This means that correct tag reception for tag j only occurs when:

$$\Pr\{j \in \mathcal{T}_R\} = \Pr\{\mathcal{T}_D = \mathcal{T}_t\}, \quad \text{where} \quad j \in \mathcal{T}_t, \tag{7}$$

where $\mathcal{T}_R$ is the set of tags correctly received at the reader side. A tag that has transmitted to the reader side can be correctly detected with probability P_D, which can be defined as:

$$P_D = \Pr\{j \in \mathcal{T}_D | j \in \mathcal{T}_t\} = \sum_k \Pr\{\widehat{\gamma}_{j,k} > \check{\gamma}_k | j \in \mathcal{T}_t\}, \tag{8}$$

and which can be read as the probability that tag j is correctly detected as active given it has transmitted a signal. Similarly, the probability of false alarm is given by:

$$P_F = \Pr\{j \in \mathcal{T}_D | j \notin \mathcal{T}_t\} = \sum_k \Pr\{\widehat{\gamma}_{j,k} > \check{\gamma}_k | j \notin \mathcal{T}_t\}, \tag{9}$$

which can be read as the probability that tag j is incorrectly detected as active when it has transmitted no signal at all.

3. Performance metrics and Markov model

The main performance metric to be used in this chapter is the average tag throughput, which can be defined as the long term ratio of correct tag readings to the total number of time-slots used in the measurement. Before providing an expression for this metric, it is first necessary to define the network state information, as well as the tag activation and tag reception probability models, and the definition of the Markov model for the dynamic analysis of an RFID network.

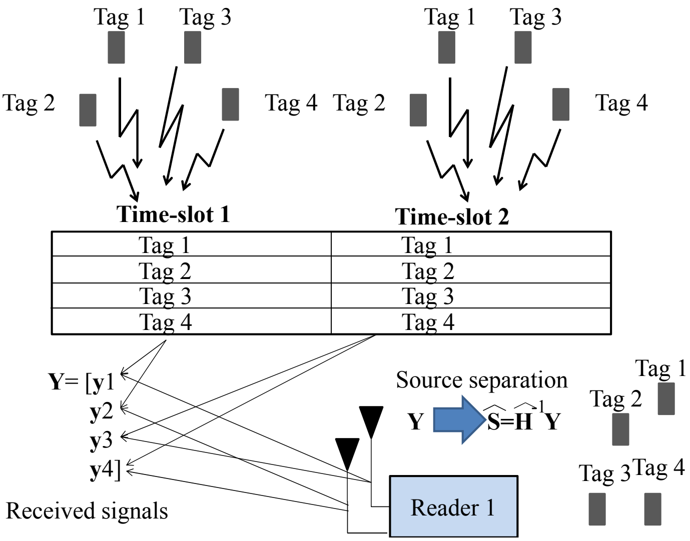

Figure 2. Example of the operation of the proposed protocol with multi-packet reception and retransmission diversity.

3.1. Network state information and tag activation model

The network state information can be defined as all the parameters that completely describe the network at any given time. In our case, the network state information $\mathcal{N}(n)$ at epoch-slot n is defined as the collection of the sets of active readers $\mathcal{R}_t(n)$ and contending tags $\mathcal{T}_t(n)$:

$$\mathcal{N}(n) = \{\mathcal{R}_t(n), \mathcal{T}_t(n)\}. \tag{10}$$

Once the network state information has been defined, we can define the probability of tag j being activated in slot n conditional on a given realization of the network state information $\mathcal{N}(n)$ and given that the tag was previously inactivated as follows:

$$Q_{j|\mathcal{N}(n)} = \Pr\{j \in \mathcal{T}_P(n+1)|\mathcal{N}(n), j \notin \mathcal{T}_P(n)\} = \Pr\{\max_k \gamma_{k,j}(n) > \tilde{\gamma}_j\}. \tag{11}$$

For convenience in the analysis, let us rewrite this tag activation probability in terms of the set of active tags $\mathcal{T}_P(n)$ by averaging over all values of $\mathcal{N}(n)$ where $\mathcal{T}_t(n) \in \mathcal{T}_P(n)$:

$$Q_{j|\mathcal{T}_P(n)} = \sum_{\mathcal{N}(n);\mathcal{T}_t(n)\in\mathcal{T}_P(n)} \Pr\{\mathcal{N}(n)\} Q_{j|\mathcal{N}(n)} \tag{12}$$

where $\Pr\{\mathcal{N}(n)\}$ is the probability of occurrence of the network state information $\mathcal{N}(n)$. This term can be calculated by considering all the combinations of active tags and readers as follows:

$$\Pr\{\mathcal{N}(n)\} = \prod_{k\in\mathcal{R}_t} p_{r,k} \prod_{m\notin\mathcal{R}_t} \overline{p}_{r,m} \prod_{j\in\mathcal{T}_t} p_{t,j} \prod_{i\notin\mathcal{T}_t} \overline{p}_{t,i} \tag{13}$$

where $\overline{(\cdot)} = 1 - (\cdot)$. This concludes the definition of the tag activation probability and the network state information.

3.2. Markov model

In order to define the Markov model for dynamic analysis of the system, let us now calculate the probability of having a set of active tags $\mathcal{T}_P(n+1)$ in epoch-slot $n+1$ conditional on having the set of active tags $\mathcal{T}_P(n)$ during the previous epoch-slot. This transition probability must consider all the combinations of tags that either enter (i.e., they are activated in epoch slot n) or leave the set of active tags (i.e., they transmit in epoch slot n). This can be expressed as follows:

$$\Pr\{\mathcal{T}_P(n+1)|\mathcal{T}_P(n)\} = \prod_{j\in\mathcal{T}_P(n),j\notin\mathcal{T}_P(n+1)} p_{t,j} \prod_{i\notin\mathcal{T}_P(n),i\in\mathcal{T}_P(n+1)} Q_{i|\mathcal{T}_P(n)} \prod_{l\notin\mathcal{T}_P(n),l\notin\mathcal{T}(n+1)} \overline{Q}_{l|\mathcal{T}_P(n)}$$

$$\times \prod_{w\in\mathcal{T}_P(n),w\in\mathcal{T}_P(n+1)} \overline{p}_{t,w}. \tag{14}$$

Let us now arrange the probability of occurrence of all the possible sets of activated tags $\Pr\{\mathcal{T}_P\}$ into a one-dimensional vector given by $\mathbf{s} = [s_0, \ldots s_{JJ}]^T$, where $(\cdot)^T$ is the transpose operator (see Fig. 3). This means that we are mapping the asymmetrical states into a linear state vector where each element represents the probability of occurrence of one different state $\Pr\{\mathcal{T}_P\}$. In the example given in Fig. 3 we have only two possible tags, where the first system state is given by both tags being active, the second state with only tag 1 as active, the third state with only tag 2 as active, and the fourth state with both tags inactive. Once these states are mapped into the state vector $\mathbf{s}$, the transition probabilities between such states ($\Pr\{\mathcal{T}_P(n+1)|\mathcal{T}_P(n)$) can also be mapped into a matrix $\mathbf{M}$, which defines the Markov model for state transition probabilities (see Fig. 3). The i, j entry of the matrix $\mathbf{M}$ denotes the transition probability between state i and state j. The vector of state probabilities can thus be obtained by solving the following characteristic equation:

$$\mathbf{s} = \mathbf{M}\mathbf{s}, \tag{15}$$

by using standard eigenvalue analysis or iterative schemes. Each one of the calculated terms of the vector $\mathbf{s}$ can be mapped back to the original probability space $\Pr\{\mathcal{T}_P\}$, which can then be used to calculate relevant performance metrics.

3.3. Tag detection model

Before calculating the tag throughput, first we must define the correct reception probability of tag j at the reader side conditional on the network state information $\mathcal{N}(n)$ as follows:

$$q_{j|\mathcal{N}(n)} = \Pr\{j \in \mathcal{T}_R(n+1)\} = \Pr\{\mathcal{T}_D = \mathcal{T}_t\}, \quad \text{where} \quad j \in \mathcal{T}_t \tag{16}$$

It is also convenient to re-write this reception probability in terms of the set of active tags $\mathcal{T}_P(n)$ by averaging over all values of $\mathcal{N}(n)$ where $\mathcal{T}_t(n) \in \mathcal{T}_P(n)$:

$$q_{j|\mathcal{T}_P(n)} = \sum_{\mathcal{N}(n);\mathcal{T}_t(n)\in\mathcal{T}_P(n)} \Pr\{\mathcal{N}(n)\} q_{j|\mathcal{N}(n)} \tag{17}$$

3.4. Tag throughput and stability

The tag throughput per resolution period can be finally calculated by adding all the contributions over the calculated probability space $\Pr\{\mathcal{T}_P\}$ using the Markov model presented in previous subsections. This can be mathematically expressed as:

$$S_j = \sum_{\mathcal{T}_P, j\in\mathcal{T}_P} \Pr\{\mathcal{T}_P\} q_{j|\mathcal{T}_P}. \tag{18}$$

Now, the throughput per time-slot can be calculated as the ratio of the throughput per resolution period to the average number of time-slots per resolution period:

$$T_j = \frac{S_j}{\sum_{\mathcal{T}_D} \Pr\{\mathcal{T}_D\} \left\lceil \frac{|\mathcal{T}_D|}{M} \right\rceil + \Pr\{\mathcal{T}_D = \emptyset\}}, \tag{19}$$

where $|\cdot|$ is the set cardinality operator and $\lceil\cdot\rceil$ is the ceil integer operator. As a measure of stability we will use the average number of activated tags, which can be calculated as follows:

$$E[|\mathcal{T}_P|] = \sum_{\mathcal{T}_P} \Pr\{\mathcal{T}_P\} |\mathcal{T}_P|. \tag{20}$$

A high number of activated tags means that stability is compromised, while a relatively low number indicates that the algorithm is more stable.

4. Optimization and results

The parameters to be optimized are the vector of reader transmission probabilities $\mathbf{p}_r = [p_{r,1}, \ldots p_{r,K}]^T$, the vector of reader transmit powers $\mathbf{P}_r = [P_{r,1}, \ldots P_{r,K}]$ and the vector of transmission probabilities of the active tags $\mathbf{p}_t = [p_{t,1}, \ldots p_{t,J}]$. The objective of the optimization is the total throughput, so the optimization problem with transmit power constraint can thus be written as follows:

$$\{\mathbf{P}_r, \mathbf{p}_t, \mathbf{p}_r\}_{opt} = \arg \max_{\{\mathbf{P}_r, \mathbf{p}_t, \mathbf{p}_r\}} \sum T_j \quad \text{s.t.} \quad \mathbf{P}_r < \mathbf{P}_{r,0} \tag{21}$$

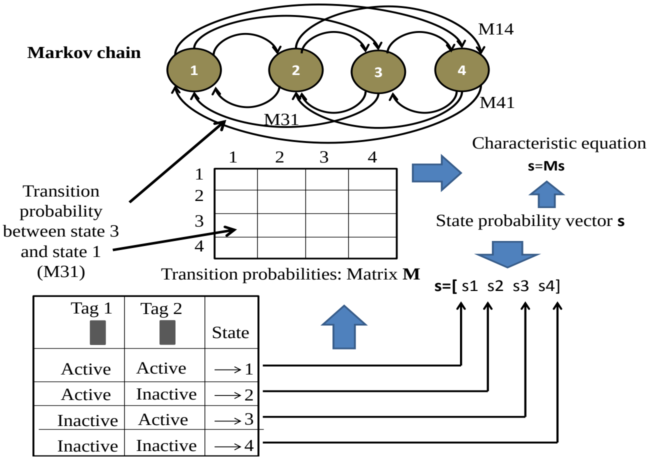

Figure 3. Example of the Markov model for a two-tag system.

Since the explicit optimization of the expressions is difficult to achieve, particularly when considering the Markov model proposed in the previous section, in this section we will simplify the optimization problem by applying the previous concepts to an ALOHA protocol implemented at the reader side. This means that tags can be only activated when the readers' transmissions are collision-free. Power levels will be fixed, and the maximum throughput performance will be investigated by simply plotting the surface versus the reader and tag transmission probabilities. At the tag side we will consider the following three options: a conventional ALOHA protocol without MPR, ALOHA with multi-packet reception (simply tagged ALOHA MPR), and the proposed scheme with retransmission diversity and multi-packet reception (tagged NDMA MPR).

Two scenarios are considered: one in which tags and readers operate in the same channel, thereby interfering with each other, and the second scenario where readers and tags operate in a synchronized manner in different channels, which eliminates the probability of collision between them. For convenience, let us consider in first instance that all tags and readers experience channel and queuing states that are statistically identical (symmetrical system). A tag activation probability of $q = 0.7$ and a tag detection probability at the reader side of $Q = 0.95$ have been used in the theoretical calculations. A probability of false alarm for the NDMA protocol has been set to $P_F = 0.01$. The results have been calculated with $J = 15$ tags and $K = 5$ readers.

Fig. 4 shows the results of average throughput $T = \sum_j T_j$ versus various values of reader and tag transmission probability p_t and p_r for a conventional ALOHA protocol without multi-packet reception ($M = 1$) and without retransmission diversity considering full interference between readers an tags. Fig. 5 shows the results of average throughput T versus various values of reader and tag transmission probability p_t and p_r for a conventional ALOHA protocol without multi-packet reception ($M = 1$) and without retransmission diversity considering no interference between readers an tags. Note how the throughput shape is considerably affected by the interference assumption between readers and tags. Fig. 6 shows the results of average number of tags versus various values of reader and tag transmission probability p_t and p_r. Fig. 7 shows the results of average throughput T

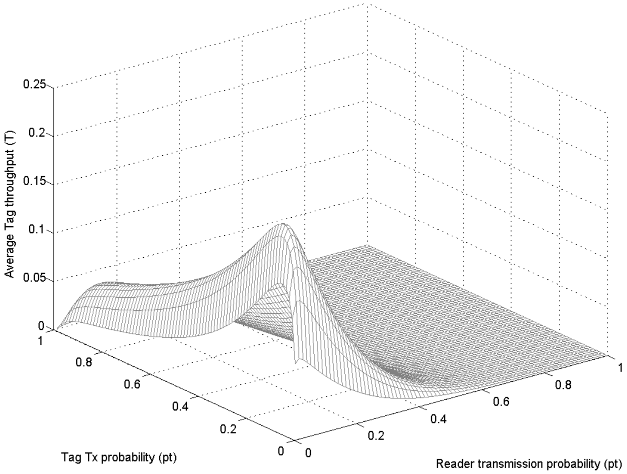

Figure 4. Throughput (T) vs. reader and tag transmissions probabilities (p_r and p_t) of a symmetrical ALOHA protocol for reader and tag anti-collision assuming interference between readers and tags.

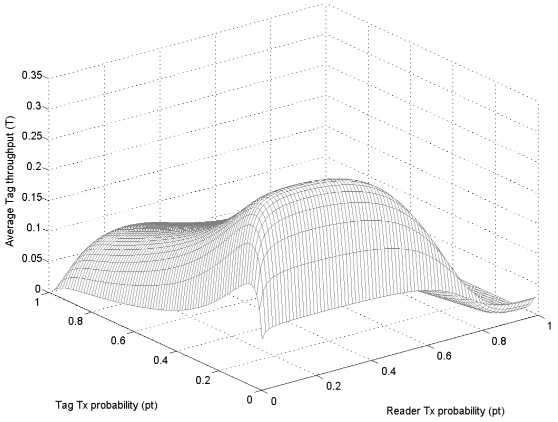

Figure 5. Throughput (T) vs. reader and tag transmissions probabilities (p_r and p_t) of a symmetrical ALOHA protocol for reader and tag anti-collision assuming no interference between readers and tags.

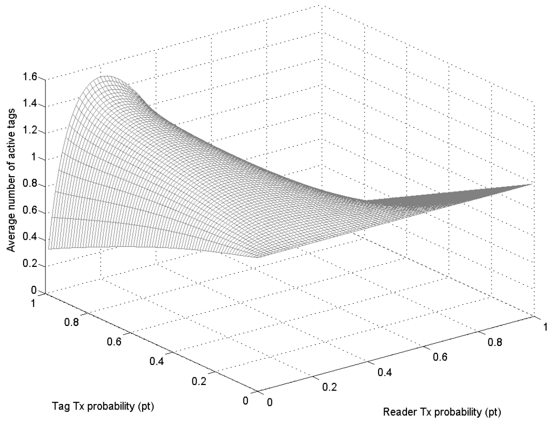

Figure 6. Average number of active tags vs. reader and tag transmissions probabilities (p_r and p_t).

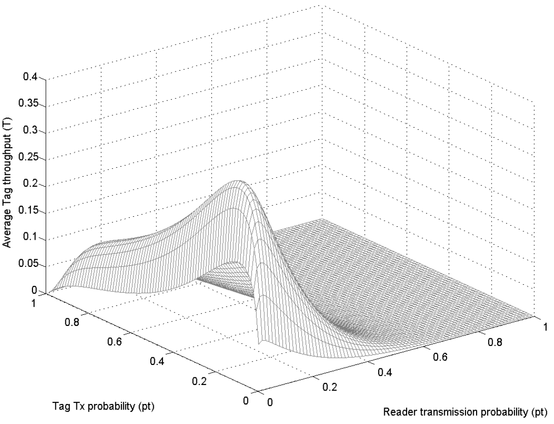

Figure 7. Throughput (T) vs. reader and tag transmissions probabilities (p_r and p_t) of a symmetrical ALOHA MPR protocol for reader and tag anti-collision assuming interference between readers and tags.

versus various values of reader and tag transmission probability p_t and p_r for a conventional ALOHA protocol with multi-packet reception ($M = 2$) and without retransmission diversity considering no interference between readers an tags. Note that the maximum throughput has been considerably improved over the conventional ALOHA protocol without MPR capabilities in Fig. 4. Similarly, Fig. 8 shows the results of average throughput T versus various values of reader and tag transmission probability p_t and p_r for a conventional ALOHA protocol with multi-packet reception ($M = 2$) and without retransmission diversity by considering no interference between readers an tags. The improvement over the algorithm without MPR in fig. 5 is considerable from almost 0.2 tags/timeslot in the case of ALOHA, to almost 0.4 tags/time-slot in the case of ALOHA MPR, and up to 0.7 tags/time-slot in the case of NDMA MPR. Fig. 9 shows the results of average throughput T versus various values

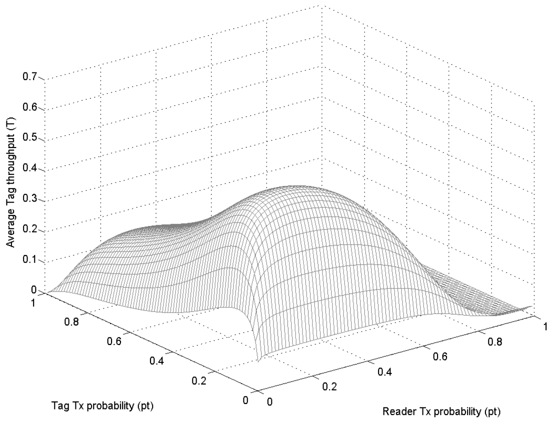

Figure 8. Throughput (T) vs. reader and tag transmissions probabilities (p_r and p_t) of a symmetrical ALOHA MPR protocol for reader and tag anti-collision assuming no interference between readers and tags.

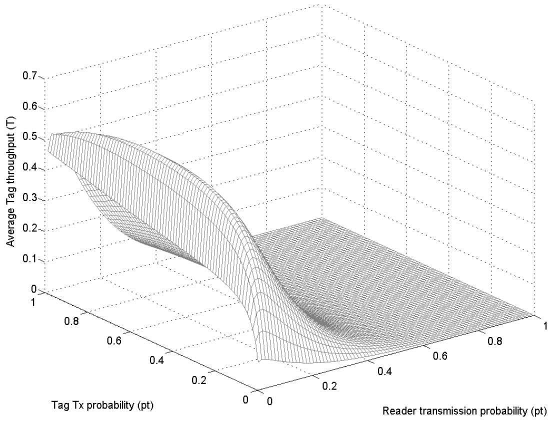

Figure 9. Throughput (T) vs. reader and tag transmissions probabilities (p_r and p_t) of a symmetrical NDMA MPR protocol for reader and tag anti-collision assuming interference between readers and tags.

of reader and tag transmission probability p_t and p_r for an NDMA MPR protocol considering interference between readers an tags, while Fig. 10 shows the results without considering interference between readers an tags. The results in Fig.9 and 10 show that the proposed NDMA MPR solution considerably outperforms its ALOHA counterparts in both scenarios: with or without interference between readers and tags.

Let us now address an asymmetrical scenario. For this purpose consider that the tag/reader space is divided into two different sets of readers and three different sets of tags. Readers and tags are working in different channels. The first and second sets of tags can only be reached by the first and second sets of readers, respectively. The third set of tags can be reached by both sets of readers. All tags have the same transmission probability p_t as well as

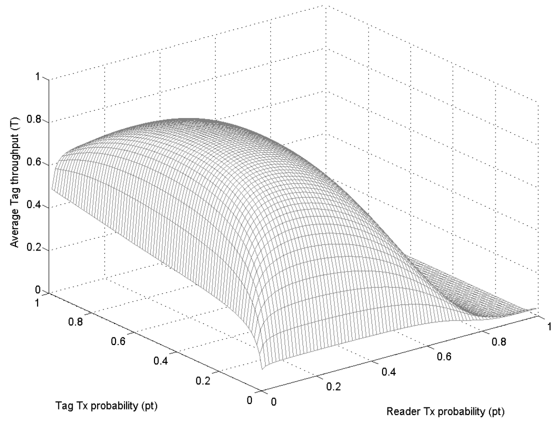

Figure 10. Throughput (T) vs. reader and tag transmissions probabilities (p_r and p_t) of a symmetrical NDMA MPR protocol for reader and tag anti-collision assuming no interference between readers and tags.

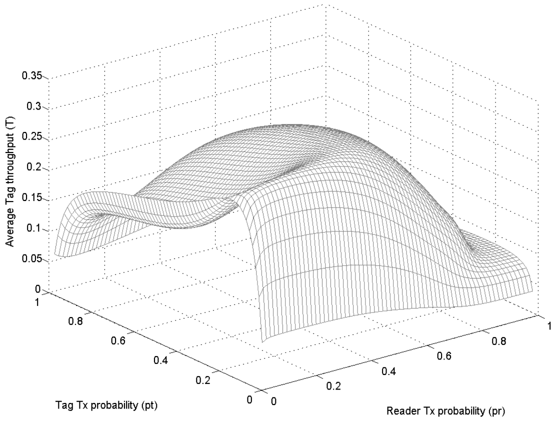

Figure 11. Throughput (T) vs. reader and tag transmissions probabilities (p_r and p_t) of an asymmetrical ALOHA protocol for reader and tag anti-collision without interference between readers and tags.

all readers transmit with the same parameter p_r. A tag activation probability of $q = 0.7$ and a tag detection probability at the reader side of $Q = 0.95$ have been used in the theoretical calculations. A probability of false alarm for the NDMA protocol has been set to $P_F = 0.01$. The results of Fig. 11 and Fig. 12 have been obtained using three groups of tags with $J_1 = 3$,$J_2 = 5$ and $J_3 = 7$ tags, and two groups of readers with $K_1 = 5$ and $K_2 = 10$ readers. While Fig. 11 shows the results of an ALOHA protocol without MPR capabilities ($M = 1$), Fig. 12 shows the results of the proposed NDMA protocol with $M = 1$. In both cases, the readers and tags are assumed to transmit in different channels, thereby avoiding interference between their transmissions. It can be observed the significant gain provided by the NDMA protocol for all values of p_t and p_r.

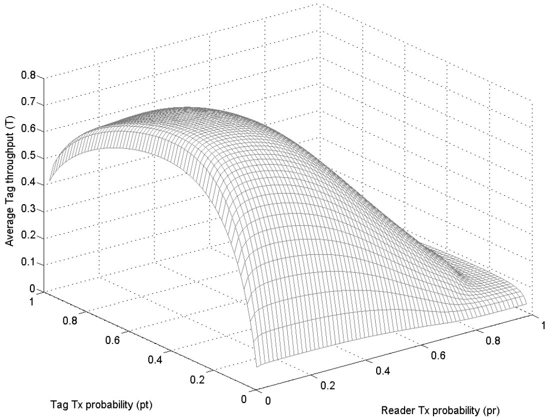

Figure 12. Throughput (T) vs. reader and tag transmissions probabilities (p_r and p_t) of an asymmetrical NDMA protocol for reader and tag anti-collision without interference between readers and tags.

5. Conclusions

This chapter presented a novel algorithm for passive RFID anti-collision based on the concepts of multi-packet reception and retransmission diversity. In addition, the design of the algorithm has been based on a new design paradigm called cross-layer design, where physical and medium access control layers are jointly designed, and where reader and tag anti-collision components are also jointly considered. The proposed Markov model is a new approach for the modeling of RFID networks, as it captures both the activation process given by the operation of readers sending requests to tags, and the tag detection process that results from tags randomly transmitting their information back to the readers that previously activated them. The results for tag throughput showed considerable improvement over conventional ALOHA solutions that have been implemented in current deployments and commercial platforms for RFID. This opens an interesting area for the design of advanced random access protocols for future RFID systems and for the internet of things.

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