Joint Design of RFID Reader and Tag Anti-Collision Algorithms: A Cross-Layer Approach

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***Abstract*—This paper investigates the potential interactions between reader and tag anti-collision algorithms of passive RFID (radio frequency identification) systems. Conventionally, reader and tag anti-collision algorithms are designed by assuming that they are independent from each other. In practice, however, readers and tags usually operate in the same frequency band. Therefore, contention between their transmissions can also potentially arise. Furthermore, reader anti-collision policies directly influence the way in which tags are activated, and thus also the way in which they collide when responding to reader's requests. In view of this and considering the growing numbers of readers and tags, independence of both schemes can not longer be considered as a realistic assumption. This paper partially fills this gap by proposing a new cross-layer framework for the joint evaluation and optimization of reader and tag anti-collision algorithms. Furthermore, the paper proposes a new approach, based on a Markov model, which allows capacity and stability analysis of asymmetrical RFID systems (i.e., when readers and tags experience different channel and queuing states). The model captures the dynamics of tag activation and tag detection processes of RFID. It also represents a first step towards a joint design of physical (PHY) and medium access control layers (MAC) of RFID. The results indicate that the proposed approach provides benefits in terms of stability and capacity over conventional solutions even when readers and tags operate in different channels. The results also provide useful guidelines towards the cross-layer design of future RFID platforms.**

***Index Terms*—RFID anti-collision algorithms, cross-layer design, random access theory.**

I. Introduction

A. 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 [1]. In passive systems, where tags reuse the energy radiated by the reader, coordination capabilities are considerably limited, thereby leading to signal collisions. Therefore, an efficient medium access control layer (MAC) is crucial to the correct operation of RFID [2].

Two types of RFID MAC collision can be distinguished: tag and reader collision. A tag collision arises when several tags simultaneously respond to the same reader request, thus causing the loss of information. To address this issue, tag anti-collision schemes such as ALOHA and binary tree algorithms are commonly employed [2]. Improvements on these solutions have been further proposed by using tag estimation methodologies [3], and modified frame structures [2]. Two types of reader collision can be also identified: multiple-reader-to-tag and reader-to-reader collision [4]. To address these issues, reader anti-collision algorithms based on scheduling or coverage control have been proposed. Typical scheduling schemes are frequency division multiple access (FDMA) [5] or listen-before-talk (LBT) [6]. Advanced schemes such as Colorwave in [7] and Pulse in [8] implement inter-reader control mechanisms to assist in collision avoidance, whereas HiQ in [9] uses analysis of collision patterns to improve scheduling. In coverage-based algorithms, we find schemes that reduce the overlapping coverage area between readers (e.g., [10]), and those that monitor interference to adapt power levels accordingly (e.g., [12]).

B. Paper contributions

Despite these advances in RFID MAC design, several issues remain open. This paper addresses some of these issues and proposes several advances over previous solutions. The paper addresses for the first time in the literature (to the best of our knowledge) the joint design of reader and tag anti-collision algorithms. To achieve this goal, a novel framework for cross-layer design of MAC and PHY (physical) layers of RFID is also proposed. Based on this framework, a Markov model is further presented for the study of capacity and stability of asymmetrical RFID systems, which is also new in the literature. More details on these objectives and the rationale behind them are next explained.

1) Joint design of reader and tag anti-collision: In conventional RFID system design, reader and tag anti-collision algorithms are considered as independent from each other. This means that reader anti-collision schemes ignore tag collisions, and viceversa, tag anti-collision schemes ignore reader collisions. The reason for this is that the number of readers is low in typical RFID applications, which means that reader collisions rarely occur. However, recent years have seen an increasing numbers of readers and tags. Also, readers and tags of passive systems usually operate in the same frequency band, which increases the probability of collision between their transmissions. Furthermore, reader anti-collision schemes directly induce tag collision patterns. Therefore, the assumption of independence of these two schemes does not longer hold. The objective of this paper is to fill this gap by studying the interactions between all the elements of a multi-tag and multi-reader RFID network.

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2) Cross-layer design in RFID: In order to achieve an accurate evaluation of multi-tag and multi-reader systems, this paper proposes a novel theoretical framework which includes relevant PHY and MAC layer parameters. Previous works on RFID MAC design have used simplistic formulations of the PHY layer which are inaccurate when modeling real-life systems. In general, cross-layer design has been scarcely used in the literature of RFID. At the MAC/PHY level, some anti-collision algorithms based on power control and reader scheduling can be considered as cross-layer solutions (e.g.,[12]), but they have not been explicitly designed with a cross-layer methodology. At upper layers, only a few cross-layer solutions using context aware analysis have been shown to significantly improve reading reliability levels (e.g., [13]) and security/privacy features (e.g.,[14]). By contrast, in conventional wireless networks cross-layer design has shown considerable benefits, particularly at the MAC/PHY level [11]. Therefore, there is a big potential in using cross-layer design to improve RFID. The proposed framework in this paper represents an initial step towards a full joint design of RFID PHY and MAC layers [15]. Stochastic reception models for correct tag activation and correct tag detection probabilities considering channel and queuing states are here proposed. This stochastic framework can also be used, for example, to describe advanced multiuser detection schemes for RFID applications.

3) Asymmetrical scenarios, results and future work: RFID MAC algorithms have been conventionally modeled in symmetrical scenarios, i.e. when all elements are statistically identical. However, this assumption is unrealistic and can lead to inaccurate design. This paper also proposes a Markov model that allows capacity and dynamic stability analysis of asymmetrical RFID systems (i.e., readers and tags have different channel and queuing states). This approach is, to the best of our knowledge, new in the literature of RFID, as it captures the dynamics of tag activation and detection processes. The results in this paper indicate that joint cross-layer optimization of reader and tag anti-collision algorithms provides considerable benefits in terms of capacity and stability even when readers and tags operate in different channels. The proposed approach was found particularly helpful in the asymmetrical case. Future work will include the use of advanced algorithms such as beam-forming, retransmission diversity, and multi-packet reception.

C. Paper organization

Section II describes the proposed framework for cross-layer optimization with the signal models for down-link and up-link reception. Section III describes the proposed metrics, the tag reception and activation probabilities and the Markov model for dynamic analysis. Section IV presents the optimization of the throughput and the results obtained in different scenarios. Finally, Section V presents the conclusions of the paper.

II. System model and cross-layer framework

Consider the slotted RFID network depicted in Fig. 1 with a set $\mathcal{R}$ of K readers, i.e., $\mathcal{R} = \{1, \dots K\}$, and a set $\mathcal{T}$ of J tags, i.e., $\mathcal{T} = \{1, \dots, J\}$. 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 (see Fig. 1). 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 $p_{r,k}$. The subset of active readers at any given time will be denoted by $\mathcal{R}_t$. Tags are activated whenever the energy received from a reader is above an activation threshold. The set of activated tags will be denoted here by $\mathcal{T}_P$ ($\mathcal{T}_P \subseteq \mathcal{T}$). These active tags proceed to transmit a backscatter signal to the readers using a randomized transmission scheme. The subset of tags that transmit a backscatter signal once they have been activated will be given by $\mathcal{T}_t (\mathcal{T}_t \subseteq \mathcal{T}_P \subseteq \mathcal{T})$, where each tag $j \in \mathcal{T}_t$ will transmit with a power level denoted by $P_{t,j}$.

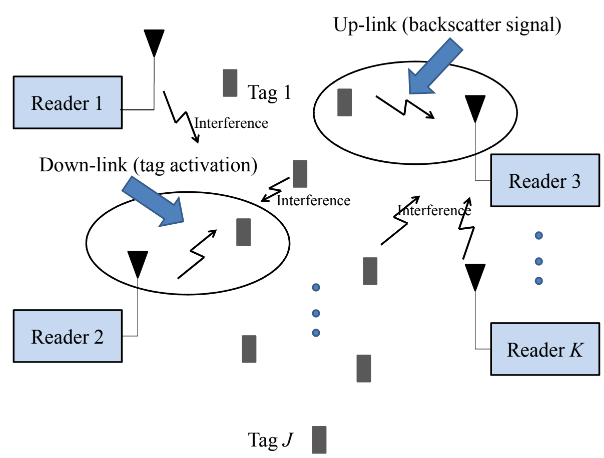

Fig. 1. Multi-tag and Multi-reader deployment scenario.

A. Tag activation: Down-link model

For convenience in the analysis, consider that the channel between reader k and tag j is given by $h_{k,j}$. Similarly, the channel between reader k and reader m is given by $g_{k,m}$, and the channel between tag i and tag j is given by $u_{i,j}$. Therefore, the signal-to-interference-plus-noise ratio (SINR) experienced by tag j due to a transmission of reader k will be denoted by $\gamma_{k,j}$, and it can be expressed as follows:

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

where $I_{r_{k,j}} = \sum_{m \in \mathcal{R}_t, m \neq k} P_{r,m}|h_{m,j}|^2$ 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 contending tags, and $\sigma_{v,j}^2$ is the noise component. If the SINR experienced by tag

j is above the tag sensitivity threshold $\widetilde{\gamma}_j$, then the tag is powered-up and is then considered as active. The probability of tag j being activated can be written as $\Pr\{j \in \mathcal{T}_P\} = \Pr\{\max_k \gamma_{k,j} > \widetilde{\gamma}_j\}$.

B. Backscattering reply and tag detection: up-link model

Once a given tag j has been activated, it starts a random transmission process to prevent collisions with other active tags. This random transmission control will be characterized by a Bernoulli process with parameter $p_{t,j}$, which is also the transmission probability. We consider the backscattering factor β_j as 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. The SINR of the signal of tag j received by reader k can then be written as:

$$\widehat{\gamma}_{j,k} = \frac{P_{t,j}|h_{j,k}|^2}{\widehat{I}_{r,k} + \widehat{I}_{t_{j,k}} + P_{r,k}\eta_k + \widehat{\sigma}^2_{v,k}}, \qquad j \in \mathcal{T}_t \qquad (2)$$

where $\widehat{I}_{r,k} = \sum_{m \neq k} P_{r,m}|g_{m,k}|^2$ is the interference created by other active readers, $\widehat{I}_{t_{j,k}} = \sum_{i \neq j} P_{t,i}|h_{i,k}|^2$ is the interference created by other active tags, η_k is the power ratio leaked from the down-link transmission chain, and $\widehat{\sigma}^2_{v,k}$ is the noise. 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 $\mathcal{T}_{D,k}$, while the probability of tag j being in $\mathcal{T}_{D,k}$ will be given by $\Pr\{j \in \mathcal{T}_{D,k}\} = \Pr\{\widehat{\gamma}_{j,k} > \check{\gamma}_k\}$.

III. Performance metrics and Markov model

The main performance metric to be used in this paper 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.

A. 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 time slot n is defined as the collection of the sets of active readers $\mathcal{R}_s(n)$ and contending tags $\mathcal{T}_t(n)$:

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

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 $\mathcal{N}(n)$ as follows:

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

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 $\mathcal{T}_t(n) \in \mathcal{T}_P(n)$:

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

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:

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

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

B. 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 time slot $n+1$ conditional on having the set of active tags $\mathcal{T}_P(n)$ during the previous time-slot. This transition probability must consider all the combinations of tags that either enter (i.e., they are activated in time slot n) or leave the set of active tags (i.e., they transmit in time slot n). This can be expressed as follows:

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

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 $\mathbf{s} = [s_0, \ldots s_{J^J}]^T$, where $(\cdot)^T$ is the transpose operator (see Fig. 2). 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. 2 we have only two possible tags, where the first system state is given by both tags as active, the second state with only tag 1 as active, the third state with only tag 2 as active, and the fourth state with none tag active. 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. 2). 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:

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

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.

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C. 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:

$$q_{j|\mathcal{N}(n)} = \Pr\{j \in \mathcal{T}_P(n+1)\} = \sum_{k \in \mathcal{R}} \Pr\{\widehat{\gamma}_{j,k}(n) > \check{\gamma}_k\}$$

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 $\mathcal{T}_t(n) \in \mathcal{T}_P(n)$:

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

D. Tag throughput and stability

The tag throughput 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:

$$T_j = \sum_{\mathcal{T}_P} \Pr\{\mathcal{T}_P\} q_{j|\mathcal{T}_P}. \tag{3}$$

As a measure of stability we will use the average number of activated tags, which can be calculated as follows:

$$E[|\mathcal{T}_P|] = \sum_{\mathcal{T}_P} \Pr\{\mathcal{T}_P\} |\mathcal{T}_P|. \tag{4}$$

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

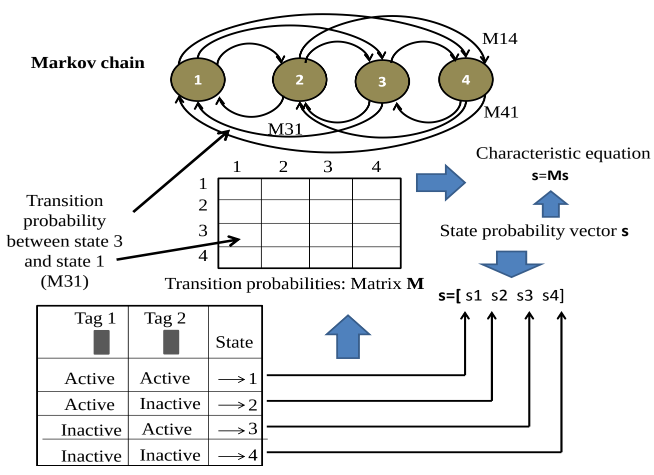

Fig. 2. Example of the Markov model for a two-tag system.

IV. Optimization and Results

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

$$\{\mathbf{P}_r, \mathbf{p}_t, \mathbf{p}_r\}_{opt} = \arg \max_{\{\mathbf{P}_r, \mathbf{p}_t, \mathbf{p}_r\}} \sum T_j$$

$$\text{subject to} \quad \mathbf{P}_r < \mathbf{P}_{r,0} \tag{5}$$

where $\mathbf{P}_{r,0}$ is the reader transmit power constraint vector. 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 both at the reader and the tag side. This means that we consider that any collision yields the loss of all information. Two different cases will be considered: one in which readers and tags transmit in orthogonal channels, i.e. no collision exists between the transmissions of readers and tags, and the second case in which readers and tags transmit at free will in the same channel, thereby leading to potential collisions. Under these assumptions, the power optimization problem reduces to simply setting the transmit power of the readers to a particular level to ensure an average tag activation and tag detection probabilities. The remaining variables to be optimized are the reader and tag transmission probabilities. To further illustrate the operation of the proposed approach, two different scenarios will be addressed: one in which all elements are statistically identical (symmetrical scenario) and another with asymmetrical features (some tags and readers have different characteristics).

A. Symmetrical case with tags and readers operating in different channels

The first scenario consists of $R = 5$ readers and $J = 15$ tags all with the same channel and queuing states (symmetrical case). Tags and readers are assumed to work in different channels. Fig. 3 displays the results of using the throughput expression in eq.(3) for various values of reader and tag transmission probabilities (p_r and p_t). MATLAB is used for calculating the results and solving explicitly the Markov chain model presented in the previous section and thus obtain the steady state vector and the throughput values. All the cases discussed in this section will use a fixed transmit power that has been set to provide the following tag activation and detection probabilities: $Q_j = 0.7$ and $q_j = 0.95$, respectively. The surface shape of the global tag throughput in Fig. 3 is slightly asymmetrical, which indicates that the optimum probabilities cannot be considered as completely independent. Consider the values of optimum transmission probability without joint design for the ALOHA protocol: $p_{t_{opt}} = 1/15$ and $p_{r_{opt}} = 1/5$, which yields a value of throughput in Fig. 3 of 0.354. By contrast, the true maximum of the system, which can be only found using joint optimization, yields 0.3558 with values $p_{t_{opt}} = 0.085$ and $p_{r_{opt}} = 0.1975$. Regarding stability, Fig. 4 shows the average number of active tags, where it can be observed that joint design can also help in driving the system towards a region with low numbers of backlogged tags. By using joint optimization, the achieved

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value for the average number of active tags is 9, whereas using the original strategy it would yield an average of 9.8 active tags. Therefore, in this case it has been observed that even in a completely symmetrical scenario where tags and readers operate in different channels, joint design also provides benefits in terms of capacity and stability.

B. Symmetrical case with tags and readers operating in the same channel

Fig. 5 displays the results for the same scenario but this time considering full interference between tags and readers. In this case, the shape is even more asymmetrical, which is consistent with the assumption of full interference between tags and readers and which indicates the increased importance of joint optimization. Consider the values of optimum transmission probability without joint design $p_{t_{opt}} = 1/15$ and $p_{r_{opt}} = 1/5$, which yields a value of throughput in Fig. 5 of 0.1789. By contrast the true maximum of the system, which can only be found using joint optimization, yields 0.2499 with values $p_{t_{opt}} = 0.035$ and $p_{r_{opt}} = 0.085$. This indicates that joint design increases its efficiency when readers and tags operate in the same channel.

C. Asymmetrical case with tags and readers operating in different channel

In the second scenario, we consider that the tag/reader space is divided into two different sets of readers and three different sets of tags (asymmetrical scenario). 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 all readers transmit with the same parameter p_r. The results displayed in Fig. 6 show that the throughput has also an irregular shape, which indicates a complex dependency between the transmission probabilities and, hence, an increased advantages of using joint optimization. The results of Fig. 6 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 $R_1 = 5$ and $R_2 = 10$ readers. The maximum of the global throughput using joint optimization is 0.4780, whereas using the conventional strategy is 0.4413. Therefore, joint optimization provides even higher gains in this asymmetrical scenario as compared to its symmetrical counterpart. According to these results, joint optimization is well suited for asymmetrical scenarios. However, in an RFID network, accurate tracking of different channels of the tags is a difficult task. A solution to this problem is to use context aware techniques that allow us to estimate tag relative positions with respect to the set of readers. Thus, it is foreseen that joint optimization will be further improved by exploiting context information acquired from different layers. In the future, RFID systems can be based on cross-layer design and then help in the acquisition of all the relevant information to carry out a more efficient optimization.

V. Conclusions

This paper addressed the joint optimization and design of reader and tag anti-collision algorithms for RFID systems. A general framework was developed for cross-layer evaluation and optimization of these two contention resolution schemes. Basic examples using ALOHA protocol have shown that in all the cases joint optimization provides benefits to global system operation in terms of stability and capacity even when readers and tags operate in different channels. The results also indicate that the gains provided by the joint optimization approach increase when the scenario deviates from the symmetrical case, which also means that in a real system deployment context aware information can be used to further improve the joint optimization process. The tools developed in this paper represent a first step towards the full joint design of MAC and PHY layers of RFID systems. The expressions derived in this paper also allow the investigation of advanced signal processing schemes for multi-packet reception which will be addressed in future works.

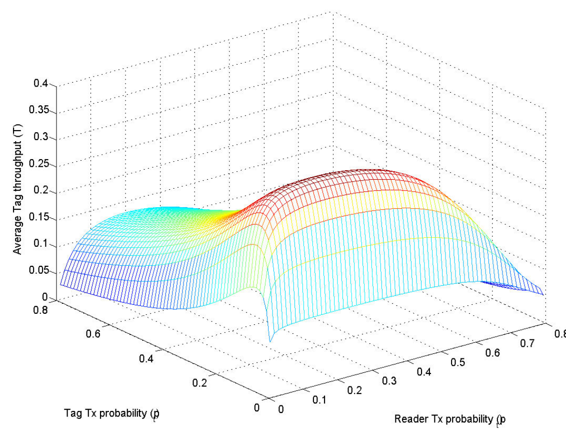

Fig. 3. Throughput (T) vs. reader and tag transmissions probabilities (p_r and p_t) of a symmetrical ALOHA protocol for reader and tag anti-collision assuming no interference between readers and tags.

References

[1] R. Weinstein, "RFID: A Technical overview and its application to the enterprise," *IT profesional,* 2005, Vol. 7, No. 3, pp. 27-33.

[2] L.A. Burdet, "RFID Multiple Access Methods," *ETH Zrich, Summer semester 2004, Seminar "Smart Environments.*

[3] D. Liu, Z. Xang, J. Tan, H. Min, and J. Wang, "ALOHA algorithm considering the slot duration difference in RFID system," *2009 IEEE International Conference on RFID*, pp. 56-63.

[4] S. Birari, "Mitigating the reader collision problem in RFID Networks with mobile readers," Master Thesis.

[5] "EPC Radio-Frequency Identity Protocols. Class-1 Generation-2 UHF RFID. Protocol for communications at 860 MHz - 960Mhz." Version1.2.0", EPC Global, 2008., http://www.epcglobalinc.org/standards/.

[6] "ETSI EN 302 208-1,2 v1.1.1, September 2004. CTAN: http://www.etsi.org"

[7] J. Waldrop, D.W. Engels, and S.E. Sarma, "Colorwave: An anticollision algorithm for the reader collision problem," *IEEE Wireless Communications and Networking Conference (WCNC), 2003.*

[8] S. Birari, "Mitigating the reader collision problem in RFID Networks with mobile readers," *13th IEEE Int. Conf. on Networks, 2005*, pp. 463-468.

 ISBN: 978-1-61208-193-9

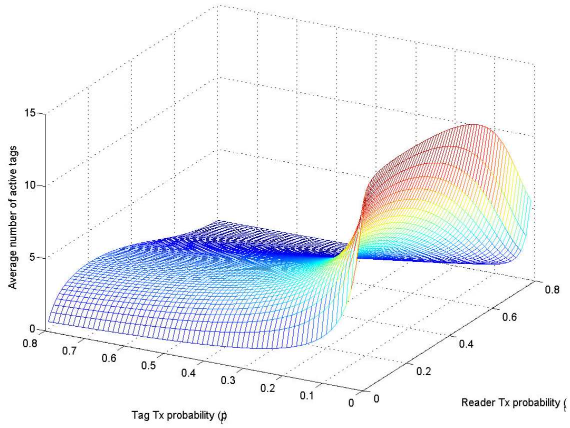

Fig. 4. Average number of active tags ($E[|\mathcal{T}_P|]$) vs. reader and tag transmissions probabilities (p_r and p_t) of a symmetrical ALOHA protocol assuming no interference between readers and tags.

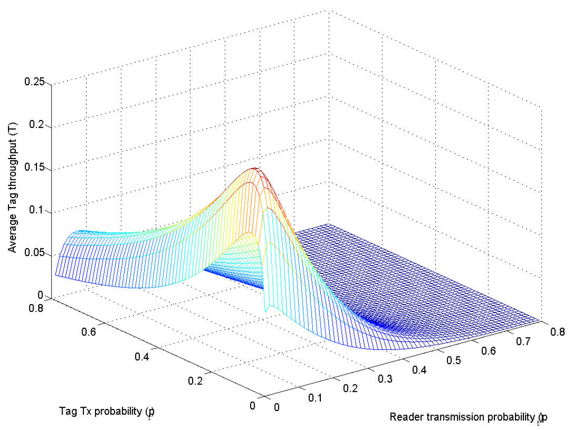

Fig. 5. Throughput (T) vs. reader and tag transmissions probabilities (p_r and p_t) of a symmetrical ALOHA protocol for reader and tag anti-collision assuming full interference between readers and tags.

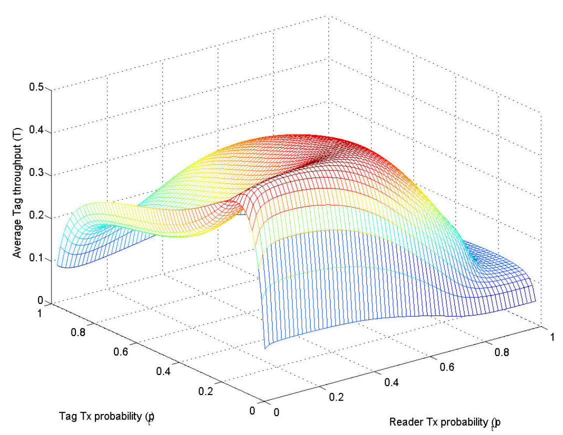

Fig. 6. Throughput (T) vs. reader and tag transmissions probabilities (p_r and p_t) of an asymmetrical ALOHA protocol for reader and tag anti-collision assuming no interference between readers and tags.

[9] K.Ho. Junius, "Solving the reader collision problem with a hierarchical q-learning algorithm," *Master's thesis,*MIT, February, 2003.

[10] S.Y. Kim and J.K. Lee "A study on control method to reduce collisions and interferences between multiple RFID readers and RFID tag," *International Conference on New Trends in Information and Service Science NISS*, 2009, pp.339-343.

[11] V. Srivastaya and M. Montani "Cross-layer design: a survey and the road ahead," *IEEE Commun. Magazine*, Vol. 43, No. 12, December 2005, pp. 112-119.

[12] K. Cha, S. Jagannathan, and D. Pommerenke " Adaptive power control with hardware implementation for wireless sensor and RFID networks," *IEEE Systems Journal,* Vol. 1, No. 2, December 2007, pp. 145-159.

[13] N. Ahmed, R. Kumar, R.S. French, and U. Ramachandran "RF^{2}ID: A Reliable Middleware Framework for RFID Deployment," *IEEE Int. Parallel and Distributed processing Symposium*, March 2007, pp. 1-10.

[14] T. Kriplean, R. Kumar, R.S. French, and U. Ramachandran "Physical Access control for captured RFID Data," *IEEE Pervasive Computing*, Vol. 6, No. 4, 2007, pp. 48-55.

[15] R. Samano-Robles and A. Gameiro "Collision resolution algorithms for RFID applications," *Asia-Pacific Microwave Conference*, 2008, pp. 1-4.