# Throughput, Stability and Fairness of RFID Anti-Collision Algorithms with Tag Cooperation

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***Abstract*—This paper addresses the design of a class of anti-collision algorithms for passive RFID (radio frequency identification) systems, where tags are allowed to cooperate by relaying (if necessary) the signals of other tags towards the destination. All the relayed signals are combined at the reader side so as to improve tag detection probabilities. The work is focused on asymmetrical scenarios where tags and readers experience different channel statistics. The objective is to include tag cooperation in RFID anti-collision algorithms. To achieve this goal, a framework for medium-access-control and physical (MAC/PHY) cross-layer design of cooperative RFID anti-collision algorithms is here presented. A tag activity model is also proposed where different tag states are initially selected according to the tag activation SINR (signal-to-interference-plus-noise ratio). Tags activated by high SINR values enter into states with relaying capabilities, whereas those with low SINR values act as simple sources of information (non-relaying state). Tags can change state depending on the number of (re)transmissions performed. A Markov model is used to calculate the system steady-state probabilities. Instability is evaluated by the number of tags in the backlog state, while fairness is evaluated by means of the Gini index. Results show that tag cooperation is useful in networks where tags with good channel states and low traffic requests cooperate with tags with bad channel states and low traffic requests.**

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

## I. Introduction

### A. RFID technology and previous works

RFID (Radio Frequency Identification) has been identified as a good candidate for enabling the concept of the Internet-of-Things (IoT). The main idea behind the concept of the IoT is to finally bridge the gap between the virtual world of computers and the physical world of objects. In RFID, a reader or interrogator requests information (via radio frequency signals) to low-cost tags or transponders [1]. These tags, which are in charge of responding to reader's requests, can be attached to objects, animals or humans, and in some cases they can sense environmental parameters such as temperature, position and speed [2]. In passive RFID, where tags reuse the energy radiated by readers, the limited coordination capabilities between the network elements leads to the problem of signal collisions. Therefore, an efficient medium access control (MAC) layer is crucial to the correct operation of RFID [3].

Two types of collision can be identified at the MAC layer of RFID: *tag* and *reader* collision. A tag collision occurs when two or more tags simultaneously respond to the same request. Anti-collision schemes such as ALOHA and binary tree algorithms are commonly employed to resolve tag collisions [3]. Tag estimation methodologies [4], and modified frame structures [3] have been proposed to improve the performance of these anti-collision algorithms. Two types of reader collision can be also identified: *multiple-reader-to-tag* and *reader-to-reader* [5]. Two types of reader anti-collision algorithms can be distinguished: those based on scheduling and those based on coverage control. Typical scheduling schemes have been subject to standardization: e.g., frequency division multiple access (FDMA) in [6], and listen-before-talk (LBT) in [7]. More advanced schemes such as Colorwave [8] and Pulse [9] implement inter-reader control mechanisms to assist in collision avoidance. These schemes have paved the way for self-organizing RFID anti-collision algorithms. Other solutions such as HiQ [10] employ an analysis of collision patterns to improve reader scheduling and thus reduce collision events in subsequent time slots. In coverage-based algorithms, we can find schemes that reduce the overlapping coverage area between readers (e.g., [11]), and those that monitor interference to adapt power levels accordingly (e.g., [12]).

### B. Open issues and objectives

Despite these recent advances in RFID MAC layer design, several issues remain open today. In particular, the last few years have seen the proliferation of advanced signal processing tools for conventional wireless networks (see [13] and [14]) that have not been fully explored in RFID. It is expected that these algorithms will improve the performance of RFID just as they improve conventional systems [15]. However, in order to support a new physical (PHY) layer, an appropriate MAC layer design is also required. This opens a wide range of MAC/PHY cross-layer design issues for RFID.

One of the potential new PHY layer schemes for RFID is known as cooperative diversity (CD). CD has been shown to improve capacity, coverage, fairness and power consumption of conventional wireless networks [20]. In networks with CD, terminals are allowed to relay the packets of other terminals. The network of relays mimics a macroscopic multiple antenna system with high diversity gains. CD in RFID has been explored only at the reader level in [17]. However, tag cooperation, to the best of our knowledge, has not been addressed yet. The main reason for this is the limited processing capabilities of passive tags, which would avoid, in principle, the use of tag-to-tag communication. However, recent developments in

[16] have shown that such tag-to-tag communication can also be achieved in passive RFID.

The objective of this paper is to include tag cooperation in the design of RFID anti-collision algorithms. In this paper it is assumed that passive tag-to-tag communication is feasible. Therefore, our focus is on the study of the consequences of cooperation at the MAC layer rather than on the demonstration of the feasibility of such tag cooperation. Recent results in [16], however, suggest that the tag PHY cooperative layer modeled in this work is feasible or is closed to be enabled by technology developments. To achieve an appropriate analysis of tag cooperative schemes, a new design paradigm, commonly known as MAC/PHY cross-layer design, is also required. MAC/PHY cross-layer design plays a crucial role in the design of conventional systems with CD. For example, the work in [18] uses CD not only to improve PHY layer performance, but also to resolve collisions at the MAC layer. Throughput and stability analysis of ALOHA with CD has been presented in [19]. A unified framework for cross-layer design in CD networks has been described in [20], and a two-transmitter two-receiver cooperative cross-layer algorithm has been proposed in [21], among several other solutions in the literature.

### C. Paper contributions

This paper proposes an extension of the framework for MAC/PHY cross-layer design of RFID systems previously presented in [1] to cope with tag cooperation capabilities. The framework includes a tag reception model suitable for MAC/PHY cooperative cross-layer design, where relaying retransmissions are requested only when the tag is not correctly detected by the destination. Reception probabilities calculated in closed-form in [22] for the particular case of Rayleigh channels are also used in this work. In addition, tag activity is modeled with different tag states that initially depend on the tag activation SINR: tags activated by a relatively high SINR are driven into a state where they are able to relay the signals of other tags in the network. By contrast, tags activated by the minimum SINR are considered to enter a state where they have no relaying capabilities, thereby acting as simple sources of information. The states of the all network, i.e. the collection of tags in their different states, are mapped into a one-dimensional Markov model that can be solved by conventional eigenvalue analysis. The solution provides the steady-state probabilities of the network, which are then used to calculate different metrics of the system, such as throughput, average number of activated tags in the backlog state, backlog delay, and fairness (by means of the Gini index). Numerical results show interesting properties of cooperative diversity in RFID networks. The modeling tools proposed in this paper, which assume an asymmetrical network deployment, and which include in the same design both reader and tag anti-collision cooperative components, also represent a novel contribution and a more realistic modeling approach of complex RFID networks. Therefore, the analytical framework developed here is envisioned for future RFID systems with large numbers of tags and readers where interference becomes a relevant issue in MAC layer design.

TABLE I
NOTATION AND SYMBOLS

| **Symbols** | **Meaning** |
|---|---|
| $\|\cdot\|$ | Absolute value and set cardinality operator |
| $\bar{(\cdot)} = 1 - (\cdot)$ | Complement to one |
| $\mathcal{R}$ | Set of available readers |
| $K$ | Number of available readers |
| $\mathcal{R}_t$ | Subset of contending readers |
| $P_{r,k}$ | Transmit power of reader $k$ |
| $p_{r,k}$ | Transmission probability of reader $k$ |
| $\mathcal{T}$ | Set of available tags |
| $J$ | Number of available tags |
| $\mathcal{T}_t$ | Subset of contending tags |
| $\mathcal{T}_P$ | Subset of activated tags |
| $\mathcal{T}_P^{(d)}$ | Subset of tags in state $d$ |
| $D$ | Maximum number of tag states |
| $\mathcal{T}_{c,j}$ | Subset of tags cooperating with tag $j$ |
| $\mathcal{T}_{D,k}$ | Subset of tags detected by reader $k$ |
| $P_{t,j}$ | Transmit power of tag $j$ |
| $p_{t,j}$ | Transmission probability of tag $j$ |
| $p_{ret,j}$ | Cooperative re-transmission probability of tag $j$ |
| $h_{k,j}$ | Channel between reader $k$ and tag $j$ |
| $g_{k,m}$ | Channel between reader $k$ and tag $m$ |
| $u_{i,j}$ | Channel between tag $i$ and tag $j$ |
| $\gamma_{k,j}$ | SINR of tag $j$ due to a transmissions of reader $k$ |
| $I_{r_{k,j}}$ | Reader interference to the signal of reader $k$ at tag $j$ |
| $I_{t_j}$ | Interference created by active tags on tag $j$ |
| $\sigma_{v,j}^2$ | Noise variance at tag $j$ |
| $\tilde{\gamma}_j^{(d)}$ | Tag activation threshold for state $d$ |
| $\beta_j$ | Backscattering factor of tags $j$ |
| $\hat{\gamma}_{j,k}$ | SINR of the signals of tag $j$ at reader $k$ |
| $\hat{I}_{r_k}$ | Reader interference on reader $k$ |
| $\hat{I}_{t_{j,k}}$ | Tag interference to the signal of tag $j$ at reader $k$ |
| $\sigma_{v,k}^2$ | Noise variance at reader $k$ |
| $\eta_k$ | Leakage ratio for reader $k$ |
| $\check{\gamma}_k$ | Detection threshold of reader $k$ |
| $R$ | Maximum number of transmissions per resolution period |
| $\xi_{j,i}$ | SINR of tag $j$ at tag $i$ |
| $I_{r,i}$ | Reader interference on tag $i$ |
| $\tilde{\gamma}_i$ | Tag detection threshold of tag $i$ |
| $\hat{\gamma}_{j,k}^{(c)}(n)$ | Cooperative SINR of tag $j$ at reader $k$ in time slot $n$ |
| $\hat{\gamma}_{j,k}^{(tot)}(n)$ | MRC SINR of tag $j$ at reader $k$ in time slot $n$ |
| $\mathcal{N}(n)$ | , Network state information in time slot $n$ |
| $Q_{j\|\mathcal{N}(n)}^{(d)}$ | Tag activation probability for state $d$ |
| $G_{j\|\mathcal{N}(n)}^{(d)}$ | Tag transition probability for state $d$ |
| $\mathbf{s}$ | Steady-state probability vector |
| $\mathbf{M}$ | Matrix transition probability |
| $q_{j\|\mathcal{N}(n)}$ | Tag detection probability |
| $q_{j\|\mathcal{N}(n)}^{(c)}$ | Cooperative tag detection probability |
| $q_{j\|\mathcal{N}(n)}^{(tot)}$ | Total cooperative tag detection probability |
| $l_{ep}$ | Length of resolution period |
| $T_j$ | Tag $j$ throughput or reading rate |
| $D_b$ | Delay |
| $F_G$ | Gini index |

### *D. Paper organization*

Section II describes the proposed framework for RFID cross-layer optimization with the signal models for down-link, up-link and cooperative 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

### *A. Scenario description and protocol operation*

Consider the slotted RFID network depicted in Fig. 1 with a set of $K$ readers denoted by $\mathcal{R} = \{1, \ldots K\}$, and a set of $J$ tags denoted by $\mathcal{T} = \{1, \ldots, J\}$. Tags are allowed to relay, if requested, the signals of other tags towards the readers of the network. At the reader side, all the copies of the relayed signal of a given tag are combined (using a maximum ratio combiner -MRC-) so as to achieve high diversity gains. In this paper it is assumed that readers have enough complexity for MRC processing. However, all expressions also apply for systems without MRC. The relaying protocol used in the tags will be decode-and-forward (DF). Four main processes can be identified in the cooperative RFID network in Fig. 1:

- *Tag activation* by the transmission of readers, also called the *down-link transmission*,
- *Backscattering response* by previously activated tags, also called *up-link transmission*,
- Tag detection by neighbor tags or *tag-to-tag communication*, and
- *Relaying* of signals by cooperative tags and the signal combining at the reader side.

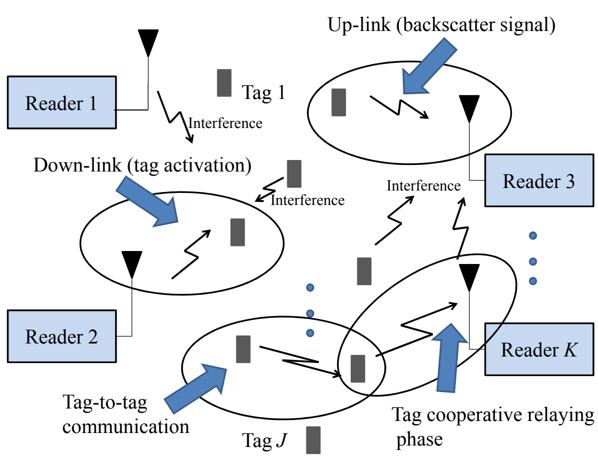



Fig. 1. Multi-tag and Multi-reader deployment scenario with cooperation between tags.

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 SINR received from a reader is above an activation threshold $\widetilde{\gamma}_j^{(0)}$. A tag will be assumed to be in $D$ possible different states according to the SINR level that was used to activate it. For example, if the SINR is above the minimum SINR threshold for activation $\widetilde{\gamma}_j^{(0)}$ and below a second SINR threshold $\widetilde{\gamma}_j^{(1)}$, where $\widetilde{\gamma}_j^{(1)} > \widetilde{\gamma}_j^{(0)}$, then the tag will only act as a source of information. On the contrary, if the SINR that activates a tag is above $\widetilde{\gamma}_j^{(d)}$ and below $\widetilde{\gamma}_j^{(d+1)}$, with $d > 1$, then the tag is allowed to retransmit either its own signal or that of another tag up to $d$ times. The set of active tags in state $d$ will be denoted here by $\mathcal{T}_P^{(d)}$, where $\mathcal{T}_P^{(d)} \subseteq \mathcal{T}$ and $d \in \{1, \ldots, D\}$. These active tags proceed to transmit a backscatter signal to the readers using a randomized transmission scheme. The set of tags that have been activated, regardless of their available energy status, is simply denoted by $\mathcal{T}_P$, where $\mathcal{T}_P = \bigcup_{d=1}^{D} \mathcal{T}_P^{(d)}$.The subset of tags that transmit a backscatter signal once they have been activated will be given by $\mathcal{T}_t$, where $\mathcal{T}_t \subseteq \mathcal{T}_P \subseteq \mathcal{T}$ and where each tag $j \in \mathcal{T}_t$ will transmit with a power level denoted by $P_{t,j}$. Whenever a tag is not correctly detected, the system proceeds to request the immediate retransmission either from the original tag or from another tag that has correctly decoded the original transmission and that has enough energy to relay a copy towards the reader(s). The cooperative retransmission probability of tag $j$ is denoted by $p_{ret,j}$, while the set of tags that have relayed a signal of tag $j$ in time slot $n$ is denoted by $\mathcal{T}_{c,j}(n)$. The maximum number of requested retransmissions is denoted by $R$. Since in cooperative protocols with half duplex constraints a packet transmission can take a random number of time-slots, the length of a cooperative phase or *epoch-slot* will denoted here by the random variable $l_{ep}$, where $0 \leq l_{ep} \leq R$. Finally, the set of tags correctly detected by reader $k$ will be denoted by $\mathcal{T}_{D,k}$.

### *B. Tag activation: Down-link model*

Let us consider that the channel between reader $k$ and tag $j$ is given by $h_{k,j}$, while 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 $k$, which is denoted here by $\gamma_{k,j}$, 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 a given tag $j$, which was initially inactive, is above the threshold $\widetilde{\gamma}_j^{(d-1)}$ and below the threshold $\widetilde{\gamma}_j^{(d)}$, then the tag is assumed to enter into state $d$. The probability of an initially inactive tag $j$ being activated to state $d$ in epoch-slot $n$ can thus be written as follows:

$$\Pr\{j \in \mathcal{T}_P^{(d)}(n) | j \in \mathcal{T}_P^{(0)}(n-1)\} = \Pr\{\widetilde{\gamma}_j^{(d-1)} < \max_k \gamma_{k,j}(n) > \widetilde{\gamma}_j^{(d)}\}, \tag{2}$$

which means that the probability of tag $j$ being activated to state $d$ is equal to the probability of the activation SINR being below $\widetilde{\gamma}_j^{(d)}$ and above $\widetilde{\gamma}_j^{(d-1)}$.

### C. Backscattering transmission: up-link model (non-cooperative)

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 $\beta_j$ 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:

$$\widehat{\gamma}_{j,k} = \frac{P_{t,j}|h_{j,k}|^2}{\widehat{I}_{r,k} + \widehat{I}_{t_{j,k}} + P_{r,k}\eta_k + \widehat{\sigma}_{v,k}^2}, \qquad j \in \mathcal{T}_t \tag{3}$$

where $\widehat{I}_{r,k} = \sum_{m \neq k} P_{r,m}|g_{m,k}|^2$ is the interference created by 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, $\eta_k$ is the power ratio leaked from the down-link transmission chain, and $\widehat{\sigma}_{v,k}^2$ is the noise at the reader side. Tag $j$ can be detected by reader $k$ if the received SINR is above a threshold denoted by $\check{\gamma}_k$. The probability of tag $j$ being detected by reader $k$ in the non-cooperative phase will be thus given by

$$\Pr\{j \in \mathcal{T}_{D,k}\} = \Pr\{\widehat{\gamma}_{j,k} > \check{\gamma}_k\}, \tag{4}$$

which means that the probability of tag $j$ being inside the set of detected tags of reader $k$ is equal to the probability of the SINR of tag $j$ at reader $k$ being above the detection threshold of reader $k$. Whenever a tag is not correctly detected by the reader(s), the system enters into a cooperative phase with a maximum of $R$ transmissions (one direct transmission and $R-1$ possible cooperative retransmissions). The cooperative retransmissions are continuously requested until the tag is correctly decoded or until the maximum number of retransmissions $R-1$ has been reached.

### D. Tag-to-tag transmission model

The SINR of the signal of tag $j$ received by tag $i$ can be written as:

$$\xi_{j,i} = \frac{P_{t,j}|u_{j,i}|^2}{I_{r,i} + I_{t_i} + \sigma_{v,i}^2}, \qquad j \in \mathcal{T}_t, \tag{5}$$

where $I_{r,i} = \sum_{m \in \mathcal{R}_t} P_{r,m}|h_{m,i}|^2$ is the interference created by active readers. Tag $j$ can be detected by tag $i$ if the received SINR is above a threshold denoted by $\widetilde{\gamma}_{i,r}$. The probability of tag $j$ being correctly detected by tag $i$ will be thus given by

$$\Pr\{\xi_{j,i} > \widetilde{\gamma}_{i,r}\}, \tag{6}$$

which indicates that the probability of tag $j$ being detected by tag $i$ is simply the probability that its SINR is above the tag detection threshold of tag $i$.

### E. Cooperative relaying phase model

Whenever a given tag is incorrectly detected by the reader, the system will request retransmission by means of an ideal feed-back channel. Tags in a relaying-able state, which have correctly decoded the original transmission and which are allowed to retransmit, proceed to do so in the following time slot. The SINR experienced by the transmission of tag $j$ received by reader $k$ in the cooperative phase is denoted by $\widehat{\gamma}_{j,k}^{(c)}$, and it is given by:

$$\widehat{\gamma}_{j,k}^{(c)} = \frac{\sum_{i \in \mathcal{T}_{c,j}} P_{t,i}|h_{k,i}|^2}{\widehat{I}_{r,k} + \widehat{I}_{t_{j,k}} + P_{r,k}\eta_k + \widehat{\sigma}_{v,k}^2}, \qquad j \in \mathcal{T}_t \tag{7}$$

Since the reader proceeds to the combining of current and previous received copies of the transmission via the MRC receiver, the total SINR at the $p$-th time slot of an epoch slot is the summation of all SINRs of the transmissions in previous time slots of the epoch slot:

$$\widehat{\gamma}_{j,k}^{(tot)}(p) = \widehat{\gamma}_{j,k} + \sum_{w=2}^{p} \widehat{\gamma}_{j,k}^{(c)}(w). \tag{8}$$

The total probability of tag $j$ being detected by reader $k$ in the cooperative phase at the $p$-th time slot will be thus given by

$$\Pr\{j \in \mathcal{T}_{D,k}\} = \Pr\{\widehat{\gamma}_{j,k}^{(tot)}(p) > \check{\gamma}_k\}, \tag{9}$$

which simply indicates the probability that the cooperative SINR is above the tag detection threshold of reader $k$. Since the relaying phases will be activated only when the previous transmissions were not correctly detected, it is convenient to rewrite the previous probability in eq.(9) indicating the statistical dependency on the incorrect reception during the previous time-slots as follows:

$$\Pr\{j \in \mathcal{T}_{D,k}\} = \Pr\{\widehat{\gamma}_{j,k}^{(tot)}(p) > \check{\gamma}_k | \widehat{\gamma}_{j,k}^{(tot)}(p-1) < \check{\gamma}_k\}. \tag{10}$$

Closed-form expressions for these conditional reception probabilities in the case of single-user transmission have been derived in [22] for Rayleigh fading channels and will be reused here to calculate performance metrics in subsequent sections.

## III. Performance metrics and Markov model

The main performance metric to be used in this paper is the average tag throughput or tag reading rate, 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 following concepts and tools: the network state information, both the tag activation and tag reception probability models, and the Markov model that will be used for for the dynamic performance analysis of the RFID network.

### A. Network state information and tag activation model

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

$$\mathcal{N}(n) = \{\mathcal{R}_t(n), \mathcal{T}_t(n)\}. \quad (11)$$

Once the network state information has been defined, we can then define the probability of tag $j$ being activated and driven into state $d$ in epoch slot $n$, given that it was inactive in the previous epoch slot and conditional on a given realization of the network state information $\mathcal{N}(n)$. This can be written, with the help of eq. (1) and (2), as follows:

$$Q^{(d)}_{j|\mathcal{N}(n)} = \Pr\{j \in \mathcal{T}^{(d)}_P(n+1)|\mathcal{N}(n), j \in \mathcal{T}^{(0)}_P(n)\} =$$

$$\Pr\{\widetilde{\gamma}^{(d-1)}_j < \max_k \gamma_{k,j}(n) > \widetilde{\gamma}^{(d)}_j\}. \quad (12)$$

Let us now define the probability that tag $j$ downgrades its state from being in state $d+x$ in epoch slot $n$ to being in state $d$ in the following epoch slot, conditional on a given realization of the network state information $\mathcal{N}(n)$. In this paper a tag transmission either in cooperative or non-cooperative mode is the only way for a tag to downgrade its state. In the cooperative phase, the number of retransmissions depends on the length of the epoch slot. These conditions can be mathematically written, with the help of eq.(6), as follows:

$$G^{(d)}_{j|\mathcal{N}(n)} = \Pr\{j \in \mathcal{T}^{(d)}_P(n+1)|\mathcal{N}(n), j \in \mathcal{T}^{(d+x)}_P(n)\} =$$

$$\begin{cases} \Pr\{l_{ep}(n) > x\}\left(p_{t,j} + \bar{p}_{t,j} p_{ret,j} \right. \\ \left. \sum_{i\in\mathcal{T}^{(d+1)}_P(n)} \Pr\{\max_k \xi_{i,j}(n) > \widetilde{\gamma}_j\}\right), \quad d = 0 \\ \Pr\{l_{ep}(n) = x\}\left(p_{t,j} + \bar{p}_{t,j} p_{ret,j} \right. \\ \left. \sum_{i\in\mathcal{T}^{(d+1)}_P(n)} \Pr\{\max_k \xi_{i,j}(n) > \widetilde{\gamma}_j\}\right), \quad d > 0 \end{cases}, \quad (13)$$

which contains all the possible transitions between the states of the network whenever a non-cooperative or cooperative transmission have been used. The common term in eq.(13) given by $p_{t,j} + \bar{p}_{t,j} p_{ret,j} \sum_{i\in\mathcal{T}^{(d+1)}_P(n)} \Pr\{\max_k \xi_{i,j}(n) > \widetilde{\gamma}_j\}$ indicates the probability that a tag transmits with probability $p_{t,j}$ plus the probability that it cooperates with any of the other tags with probability $\bar{p}_{t,j} p_{ret,j}$ given that it has correctly detected any of the tags that requires cooperation with probability $\sum_{i\in\mathcal{T}^{(d+1)}_P(n)} \Pr\{\max_k \xi_{i,j}(n) > \widetilde{\gamma}_j\}$. In the case that $d = 0$ we assume that the length of the cooperative epoch $\Pr\{l_{ep}(n) > x\}$ has exceeded the available number of transmissions of tag $j$ and thus the tag boils down to state zero or to the inactive state. In the case that $d > 0$ we assume that the length of the epoch is exactly equal to the difference between the two tag states $\Pr\{l_{ep}(n) = x\}$. Therefore, this expression contains the behavior of the tags that have overheard the transmission of the other tags and that proceed to act as cooperative relays with a randomized transmission process. For convenience in the analysis, let us rewrite these probabilities in terms of the set of active tags $\mathcal{T}_P(n)$ by averaging over all values of $\mathcal{N}(n)$ where $\mathcal{T}_t(n) \in \mathcal{T}_P(n)$:

$$Q^{(d)}_{j|\mathcal{T}_P(n)} = \sum_{\mathcal{N}(n);\mathcal{T}_t(n)\in\mathcal{T}_P(n)} \Pr\{\mathcal{N}(n)\} Q^{(d)}_{j|\mathcal{N}(n)}, \quad (14)$$

and

$$G^{(d)}_{j|\mathcal{T}_P(n)} = \sum_{\mathcal{N}(n);\mathcal{T}_t(n)\in\mathcal{T}_P(n)} \Pr\{\mathcal{N}(n)\} G^{(d)}_{j|\mathcal{N}(n)}, \quad (15)$$

where $\Pr\{\mathcal{N}(n)\}$ is the probability of occurrence of a given realization 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:

$$\Pr\{\mathcal{N}(n)\} = \prod_{k\in\mathcal{R}_t} p_{r,k} \prod_{m\notin\mathcal{R}_t} \bar{p}_{r,m} \prod_{j\in\mathcal{T}_t} p_{t,j} \prod_{i\notin\mathcal{T}_t} \bar{p}_{t,i} \quad (16)$$

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

### B. Markov model

In order to define the Markov model for dynamic performance analysis, 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 $n$) with probability $Q^{(d)}_{j|\mathcal{T}_P(n)}$ or leave the different sets of active tags in their possible different states (i.e., they transmit once or more in epoch slot $n$) with probability $G^{(d)}_{j|\mathcal{T}_P(n)}$. This can be expressed as follows:

$$\Pr\{\mathcal{T}_P(n+1)|\mathcal{T}_P(n)\} = \prod_{j\in\mathcal{T}^{(0)}_P(n), j\notin\mathcal{T}^{(0)}_P(n+1)} p_{t,j} \times$$

$$\prod_{d=1}^{D} \prod_{i\in\mathcal{T}^{(0)}_P(n), i\in\mathcal{T}^{(d)}_P(n+1)} Q^{(d)}_{i|\mathcal{T}_P(n)} \prod_{l\in\mathcal{T}^{(0)}_P(n), l\in\mathcal{T}^{(0)}_P(n+1)} \overline{Q}^{(d)}_{l|\mathcal{T}_P(n)}$$

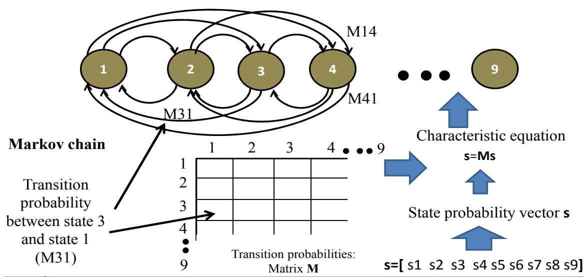
$$\prod_{d=1}^{D-1} \prod_{i\in\mathcal{T}^{(d+1)}_P(n), i\in\mathcal{T}^{(d)}_P(n+1)} G^{(d)}_{i|\mathcal{T}_P(n)}$$

$$\times \prod_{l\in\mathcal{T}^{(d+1)}_P(n), l\in\mathcal{T}^{(d+1)}_P(n+1)} \overline{G}^{(d)}_{l|\mathcal{T}_P(n)} \quad (17)$$

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 $\mathbf{s} = [s_0, \dots s_{J^J}]^T$, 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 tags, where the first system state is given by both tags being active and in a relaying state, while in the second state only tag 1 is active in a relaying state and tag 2 is also active but in a non-relaying state. The remaining states constitute all possible combinations of the states of the two tags in the system. 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:

$$\mathbf{s} = \mathbf{M}\mathbf{s}, \tag{18}$$

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 as shown in the following subsection.




| State | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| Tag 1 | Active (r) | Active (r) | Active (r) | Active (s) | Active (s) | Active (s) | Inactive | Inactive | Inactive |
| Tag 2 | Active (r) | Active (s) | Inactive | Active (r) | Active (s) | Inactive | Active (r) | Active (s) | Inactive |

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

### C. Tag detection model

Before calculating the tag throughput, first we must define the correct reception probability of tag $j$ without cooperation, conditional on the network state information $\mathcal{N}(n)$. This reception probability is given, considering eq.(4), by:

$$q_{j|\mathcal{N}(n)} = \Pr\{j \in \mathcal{T}_D(n+1)\} = \sum_{k\in\mathcal{R}} \Pr\{\widehat{\gamma}_{j,k} > \check{\gamma}_k\}, \tag{19}$$

which indicates the probability that the SINR of tag $j$ is above the detection threshold of one of the existing readers in $\mathcal{R}$. Similarly, the reception probability of tag $j$ during the cooperative phase in the $p$-th time slot of an epoch slot can be written, considering eq.(10),as:

$$q^c_{j|\mathcal{N}(n)}(p) = \Pr\{j \in \mathcal{T}_D(n+1)\} = \sum_{k\in\mathcal{R}} \Pr\{\widehat{\gamma}^{(tot)}_{j,k}(p) > \check{\gamma}_k | \widehat{\gamma}^{(tot)}_{j,k}(p-1) < \check{\gamma}_k\} \tag{20}$$

Now, the total reception probability in epoch slot $n$, considering the adaptive activation of the cooperative phase when detection in the previous transmissions have failed, can be calculated, with the help of eq.(20) and eq.(19), as follows:

$$q^{(tot)}_{j|\mathcal{N}(n)} = q_{j|\mathcal{N}(n)} + \bar{q}_{j|\mathcal{N}(n)} \sum_{m=1}^{R} \prod_{p=1}^{m-1} \bar{q}^c_{j|\mathcal{N}(n)}(p) q^c_{j|\mathcal{N}(n)}(m), \tag{21}$$

which is simply the summation of all cooperative cases with a maximum of $R$ (re)transmissions. Similarly, the average length of an epoch-slot given the transmission of tag $j$ can be calculated as:

$$l_{ep,j|\mathcal{N}(n)} = q_{j|\mathcal{N}(n)} + \bar{q}_{j|\mathcal{N}(n)} \sum_{m=1}^{R} m \prod_{p=1}^{m-1} \bar{q}^c_{j|\mathcal{N}(n)}(p) q^c_{j|\mathcal{N}(n)}(m) \tag{22}$$

It is also convenient to re-write these two previous expressions (eq.(21) and eq.(22)) in terms of the set of active tags $\mathcal{T}_P(n)$ by averaging over all values of $\mathcal{N}(n)$ where $\mathcal{T}_t(n) \in \mathcal{T}_P(n)$, which leads to:

$$q^{(tot)}_{j|\mathcal{T}_P(n)} = \sum_{\mathcal{N}(n);\mathcal{T}_t(n)\in\mathcal{T}_P(n)} \Pr\{\mathcal{N}(n)\} q^{(tot)}_{j|\mathcal{N}(n)}(n) \tag{23}$$

and

$$l_{ep,j|\mathcal{T}_P(n)} = \sum_{\mathcal{N}(n);\mathcal{T}_t(n)\in\mathcal{T}_P(n)} \Pr\{\mathcal{N}(n)\} l_{ep,j|\mathcal{N}(n)}(n) \tag{24}$$

### D. Tag throughput, stability and backlog delay

The correct tag detection probability per epoch slot can be obtained by adding all the contributions over the probability space $\Pr\{\mathcal{T}_P\}$ previously calculated with the help of the Markov model in eq.(18). This calculation can be mathematically expressed, using eq.(23), as follows:

$$S_j = \sum_{\mathcal{T}_P, j\in\mathcal{T}_P} \Pr\{\mathcal{T}_P\} p_{t,j} q^{(tot)}_{j|\mathcal{T}_P}. \tag{25}$$

The average length of an epoch slot in the steady state can then be calculated over the probability space as:

$$L = \sum_{\mathcal{T}_P} \Pr\{\mathcal{T}_P\} \left( \sum_{j\in\mathcal{T}_P} l_{ep,j|\mathcal{T}_P(n)} + \prod_{i\in\mathcal{T}_P} \bar{p}_i \right), \tag{26}$$

where the term $\prod_{i\in\mathcal{T}_P} \bar{p}_i$ accounts for the contribution of one time slot when non of the tags has transmitted. Finally, the throughput of tag $j$ can be obtained as the ratio of the correct tag detection probability per epoch-slot from eq.(25) to the average length of an epoch in the steady state from eq.(26):

$$T_j = \frac{S_j}{L} \tag{27}$$

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

$$E[|\mathcal{T}_P|] = \sum_{\mathcal{T}_P} \Pr\{\mathcal{T}_P\} |\mathcal{T}_P|. \tag{28}$$

A high number of active tags means that stability is compromised, while a relatively low number indicates that the algorithm is more stable. The average backlog delay can also be calculated, using an extension of Little's theorem as in [23], as the ratio of the average number of backlogged tags from eq.(28) to the outgoing traffic in eq.(25) [23]:

$$D_b = \frac{E[|\mathcal{T}_P|]}{\sum_j S_j}. \tag{29}$$

### E. Fairness

In this paper we will evaluate fairness by means of the Gini index, which is a metric commonly used in the area of economics. The index can be mathematically written as [24]:

$$F_G = \frac{\sum_j \sum_{k \neq j} |T_j - T_k|}{2J \sum_j T_j} \tag{30}$$

A value of the Gini index close to zero means the highest degree of fairness, while a value close to one is related to a worsening of fairness conditions.

## IV. Results

Let us now present some graphical results that will demonstrate the benefits of the proposed approach. We consider a scenario with $K = 5$ readers and two groups of tags. The first group has $J_1 = 4$ tags and the second $J_2 = 3$ tags. Tags inside the same group have the same channel statistics, while tags across different groups have different channel statistics. For convenience in the analysis we consider that the maximum number of cooperative retransmissions is 1 or $R = 2$. This also means that only two active states for tags ($D = 2$) will be considered: A relaying state and a non-relaying state. To illustrate the benefits of the proposed approach we will consider ALOHA operation rules both at the reader and tag sides. This means that only transmissions without collision will be considered as useful. In addition, all readers and tags will use the same transmission and retransmission parameters. The idea behind these assumptions is to simplify calculation while preserving some asymmetrical aspects that are addressed by the proposed approach. Tags in the first group are activated with a probability of $Q^{(1)} = 0.1$ to state 1, and with probability $Q^{(2)} = 0.5$ to state 2. Tags in the second group will be assumed to have activation probabilities $Q^{(1)} = 0.2$ and $Q^{(2)} = 0.3$. Non-cooperative reception probabilities for the first group will be given by $q = 0.6$, while for the second one a value of $q = 0.92$ will be used. Cooperative reception between tags will be given by a probability of $q_{coop} = 0.94$. Finally, tags in the relaying able state that have correctly detected the transmission of another tag and that have received the indication from the set of readers to relay a copy, will do it with a probability of $p_{rep} = 0.9$.

Figure 3 illustrates the 3-dimensional perspective of the tag throughput in the case of the cooperative ALOHA protocol versus the probabilities of transmission of tags ($p_t$) and readers ($p_r$). The non-cooperative case is illustrated in Fig. 4. The gain of the cooperative case over the non-cooperative case is displayed in Figure 5, where we can observe that the cooperative scheme provides gains for almost all values of transmission probabilities. This confirms that tag cooperative schemes provide some useful gains for the operation of the system. In terms of the number of backlogged users, Figure 6 and Figure 7 display the results for the cooperative and non-cooperative case, respectively, for users in state 1. For users in state 2, the results are displayed in Figure 8 and Figure 9, while the combined state 1 and state 2 is displayed in Figure 10 and Figure 11. It can be observed only a slight improvement in the case of the cooperative cases at low values of tag and reader transmission probabilities. This effect on the improvement of stability features is more evident in Figure 12 and Figure 13 for the backlog delay of the cooperative and non-cooperative schemes, respectively. The gain in delay reduction in Figure 14 confirms that cooperative schemes experience a reduction of the backlog delay which is useful for improving the stability of the system. Finally, in terms of the fairness indicator, Figure 15 and Figure 16 display the results of the Gini index for the cooperative and non-cooperative case, respectively. It can be observed, particularly in Figure 17, that the relative gain in fairness is slightly improved for the cooperative case, particularly for values with high load or high transmission probability.

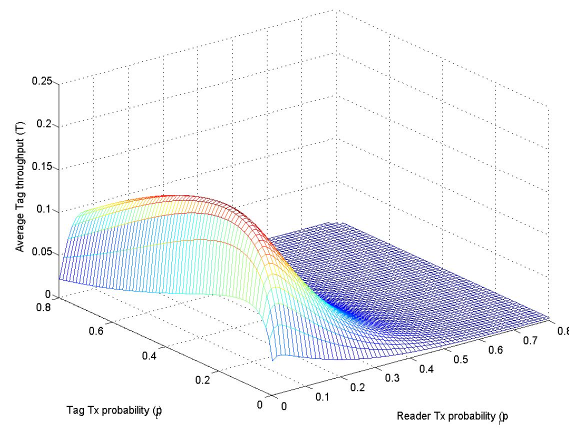



Fig. 3. Throughput ($T$) vs. reader and tag transmissions probabilities ($p_r$ and $p_t$) cooperative ALOHA.

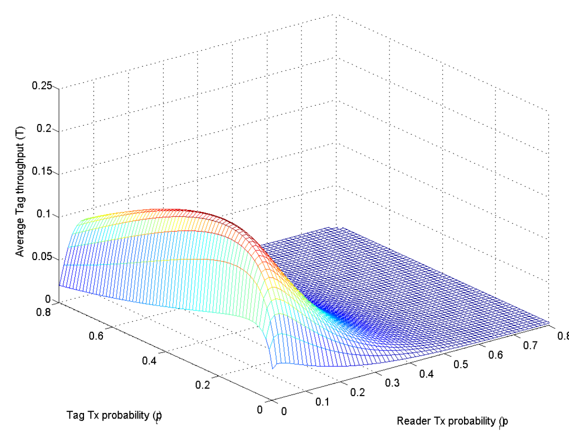



Fig. 4. Throughput ($T$) vs. reader and tag transmissions probabilities ($p_r$ and $p_t$) non-cooperative ALOHA.

## V. Conclusions

This paper has provided a framework for the MAC-PHY cross-layer design and optimization of RFID systems with tag cooperation. In addition, the modeling of the tag activity allows for the characterization of different energy harvesting capabilities. This energy harvesting feature allows some of

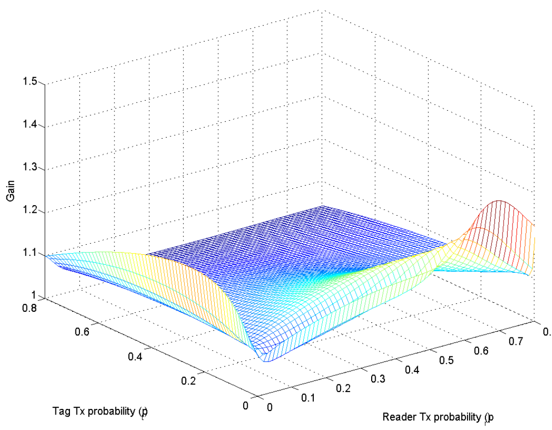



Fig. 5. Throughput Gain.

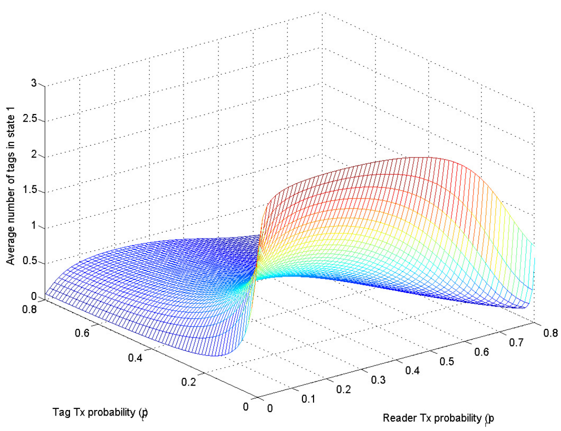



Fig. 6. Average number of active tags ($E[|\mathcal{T}_P^{(1)}|]$) in state 1 vs. reader and tag transmissions probabilities ($p_r$ and $p_t$) cooperative ALOHA.

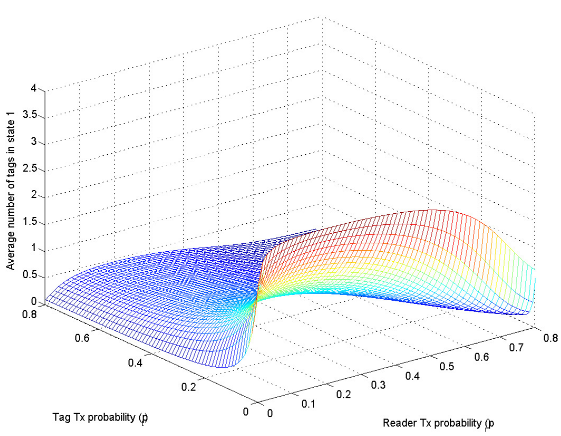



Fig. 7. Average number of active tags ($E[|\mathcal{T}_P^{(1)}|]$) in state 1 vs. reader and tag transmissions probabilities ($p_r$ and $p_t$) non-cooperative ALOHA.

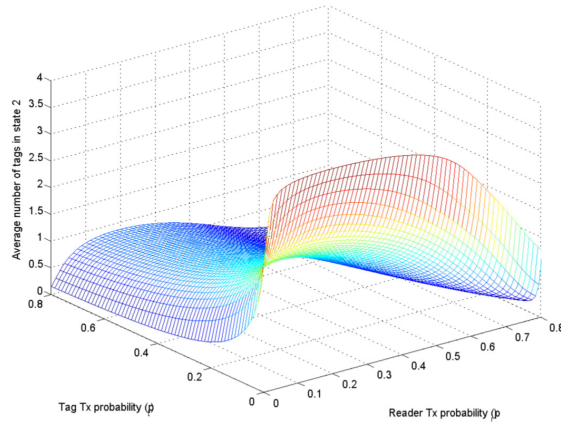



Fig. 8. Average number of active tags ($E[|\mathcal{T}_P^{(2)}|]$) in state 2 vs. reader and tag transmissions probabilities ($p_r$ and $p_t$) cooperative ALOHA.

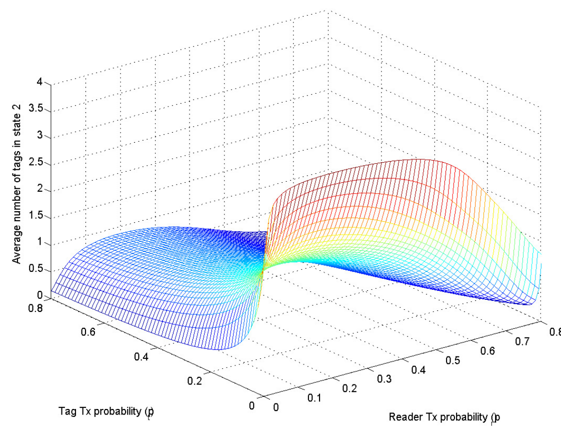



Fig. 9. Average number of active tags ($E[|\mathcal{T}_P^{(2)}|]$) in state 2 vs. reader and tag transmissions probabilities ($p_r$ and $p_t$) non-cooperative ALOHA.

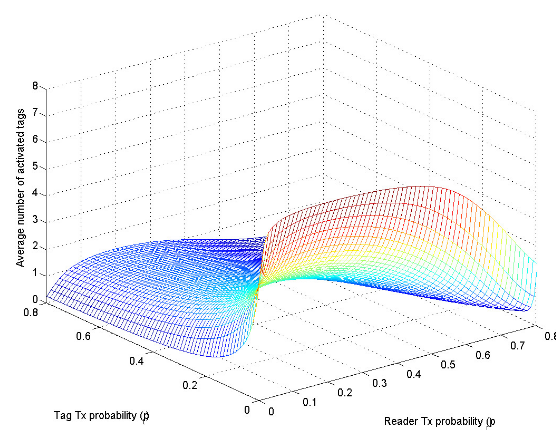



Fig. 10. Average number of active tags ($E[|\mathcal{T}_P|]$) in state 1 and 2 vs. reader and tag transmissions probabilities ($p_r$ and $p_t$) cooperative ALOHA.

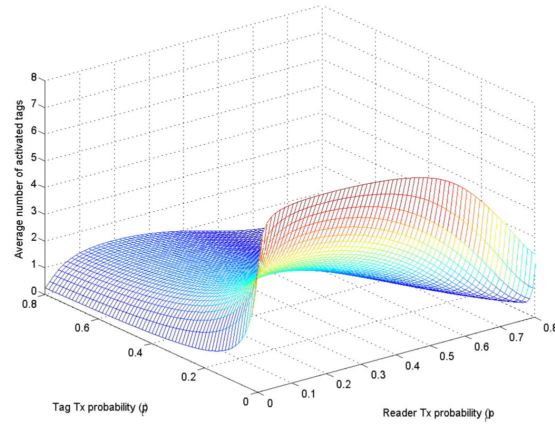



Fig. 11. Average number of active tags ($E[|\mathcal{T}_P|]$) in state 1 and 2 vs. reader and tag transmissions probabilities ($p_r$ and $p_t$) non-cooperative ALOHA.

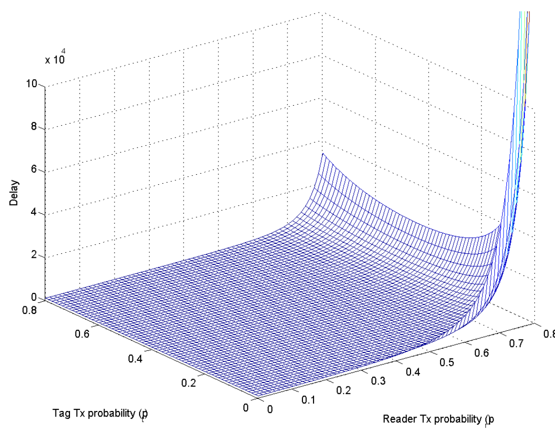



Fig. 12. Average Backlog delay ($D_b$) vs. reader and tag transmissions probabilities ($p_r$ and $p_t$) of cooperative ALOHA.

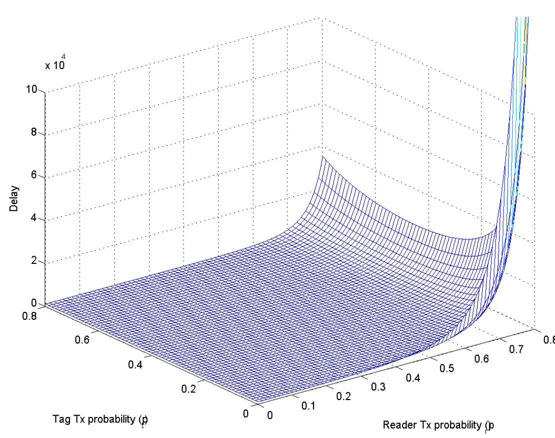



Fig. 13. Average Backlog delay ($D_b$) vs. reader and tag transmissions probabilities ($p_r$ and $p_t$) of non-cooperative ALOHA.

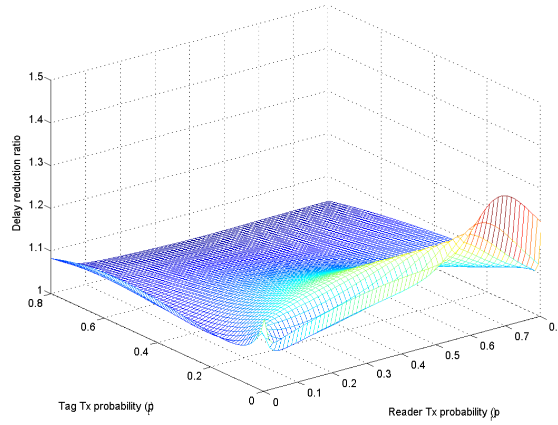



Fig. 14. Average Backlog delay reduction gain.

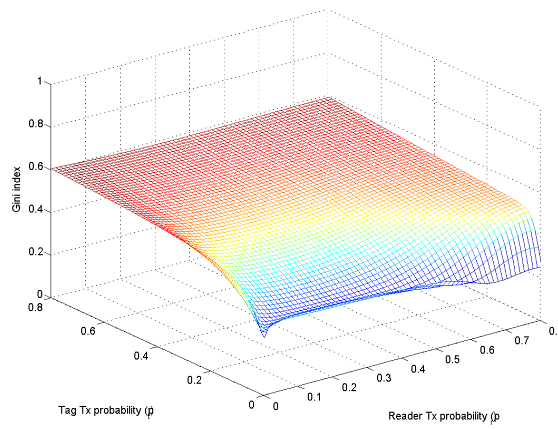



Fig. 15. Gini fairness Indicator ($F_G$) vs. reader and tag transmissions probabilities ($p_r$ and $p_t$) of cooperative ALOHA.

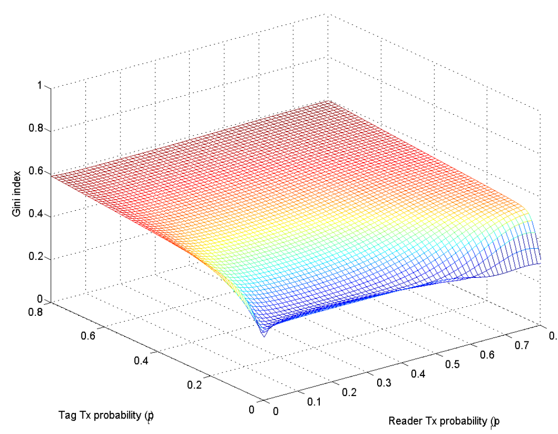



Fig. 16. Gini fairness Indicator ($F_G$) vs. reader and tag transmissions probabilities ($p_r$ and $p_t$) of non-cooperative ALOHA.

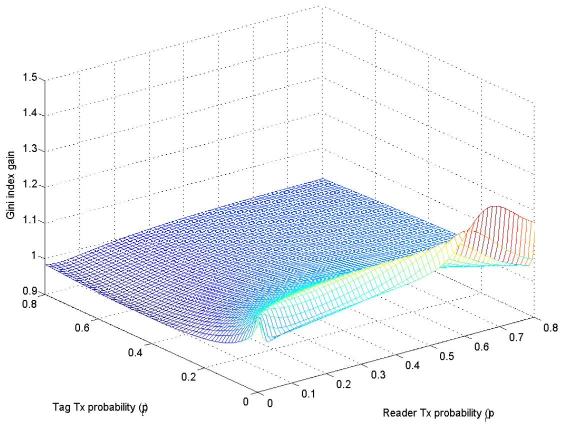



Fig. 17. Gini fairness Indicator gain.

the tags with the larger level of harvested energy to act as relays for other tags with less favored conditions. The model proposed here includes both the contention of the readers to activate the tags and the contention process of the tags to reply to the network of readers. This approach is novel in RFID while being more accurate as we can now shed light on how the processes of activation and detection of tags of RFID occur. The proposed Markov model for asymmetrical systems allows for investigation of stability aspects and dynamic performance assessment. Illustrative results with an ALOHA protocol show that tag cooperation provide general improvements in terms of throughput, stability, backlog delay and fairness over its non-cooperative counterparts. These results pave the way for more advanced cooperation algorithms with improved physical layer processing. The framework developed here can be easily upgraded to cope with new schemes at the physical and medium access layers of RFID and potentially for systems with sensors that will be relevant in the future Internet of Things.

## REFERENCES

[1] R. Samano-Robles and A. Gameiro, "Joint Design of RFID reader and tag anti-collision algorithms: a cross-layer approach," *International Conference on Digital Technologies*, Chamonix, France, 2012.

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

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

[4] 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.

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

[6] "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/.

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

[8] 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.*

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

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

[11] 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.

[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] L. Tong, V. Naware and P. Venkitasubramaniam, "Signal Processing in Random Access," *IEEE Signal Processing Magazine, Special issue on Signal processing for networking: An integrated approach* , vol. 21, no. 5, Sep. 2004, pp. 29-39.

[14] 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.

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

[16] Nikitin P.V, et al. "Passive tag-to-tag communication," *IEEE International conference on RFID, 2012*, pp. 224-231.

[17] S. Hong, et al, "ISO/IEC 18000-7 based on RFID multihop relay system," *IEEE 2009*

[18] L. Dong and A.P. Petropulu, "Multichannel ALLIANCES: A cooperative cross-layer scheme for wireless networks," *IEEE Transactions on Signal Processing*, Vol.56, No. 2, pp. 771-784, 2008.

[19] R. Samano-Robles and A. Gameiro, "A Slotted-ALOHA protocol with cooperative diversity," *4th annual Wireless Internet Conference WICON 2008*, Maui, Hawai.

[20] W.Chen, L. Dai, K.B. Letaief, and Z. Cao "A unified cross-layer framework for resource allocation in cooperative networks," *IEEE Transactions on Wireless Commun.,* vol 7, no.8, pp.3000-3012, 2008.

[21] Y. Zhou, J. Liu, C. Zhai, and L. Zheng, "Two-transmitter two-receiver Cooperative MAC protocol: cross-layer design and performance analaysis," *IEEE Trans. on Vehicular Tech.,* vol. 59, no. 8, pp. 4116-27, 2010.

[22] R. Samano-Robles and A. Gameiro, "A packet reception model for cooperative diversity in wireless multi-cell networks," *International Conference on Consumer Electronics*, Berlin, Germany, September 2011.

[23] F. Tobagi and L. Kleinrock "Packet switching in radio channels: part IV–stability considerations and dynamic control in carrier sense multiple access," *IEEE Transactions on Communications*, Vol. 25, No. 10, 1977, pp. 1103-1119.

[24] "Wolfram Mathworld Gini coefficient definition:" Available at http://mathworld.wolfram.com/GiniCoefficient.html