Advanced Collision Recovery Receiver for RFID

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***Abstract*—In this paper, we focus on a substantial throughput increase of a Radio Frequency Identification (RFID) multi antenna system. We investigate the influence of the channel estimation and the receiver structure on the theoretical throughput of Framed Slotted Aloha (FSA) based RFID systems. We propose an increase of the theoretical throughput by resolving collisions and acknowledging more than one tag per slot. Furthermore, in order to profit of such increase, we suggest a collision recovery method through successive interference cancellation and projection of the constellation into the orthogonal subspace of the interference. The performance of the proposed method is analysed by means of simulations.**

***Keywords*-Radio Frequency Identification (RFID); Framed Slotted Aloha; Collision Recovery; Channel Estimation;**

I. Introduction

Radio Frequency Identification (RFID) is an identification technology that wirelessly transmits the identity of a tag that is attached to an object or a person. If tags respond simultaneously to a reader, a collision at the air interface occurs, the information is discarded and the throughput decreases. Our research is focused on passive Ultra High Frequency (UHF) RFID and Framed Slotted Aloha (FSA) as defined in [1], leaving the existing standard unchanged as much as possible.

Without Collision Recovery (CR), only the slots with a single tag response (singleton) can be decoded successfully and the maximal throughput in FSA is achieved when the frame size is the same as the tag population size [2]. The maximal throughput in that scenario is 0.368. However, the reader does not know the tag population size and has to estimate it. In [3] the exact number of tags participating in a collision is extracted using the physical layer architecture of a reader. It is possible to increase the throughput by using the information from collisions, not just to discard it. In that way, the optimal frame size is shorter and the tags that are in the reader range can be inventoried faster. In [4] Angerer et al. demonstrated how to recover from collisions of two tags on the physical layer and how to identify tags successfully even in case of a collision. They achieved an expected throughput increase of approximately 1.6 times the throughput of a conventional reader with the proposed zero-forcing and interference cancellation receiver architecture for an RFID reader. In [5] Bletsas et al. took into account the FM0 encoding characteristics and its inherent memory and derived a single antenna detection scheme for simultaneous transmission of two tags. Furthermore, they have calculated how much time can be saved when two tag detection is utilized. In [6] authors analysed the achievable increase in throughput of a system that can recover from collisions at the physical layer. They showed that with collision recovery and acknowledgement of multiple tags per slot, the throughput can be increased significantly. Additionally, they proposed receivers for the physical layer collision recovery that require channel estimation. They showed that in the proposed channel estimation and single antenna receivers, only collisions of two tags can be recovered. Furthermore, multiple antenna receivers with perfect channel knowledge are capable of recovering from a collision of a number of tags that is less than or equal to the number of receiving antennas N_{RA}. In [7], we presented an extension of the proposed model to more receiving antennas and managed to separate up to R tags as long as that number is less than or equal to the collision recovery factor $M = 2N_{RA}$ and the channel is known to the receiver. With that model, we achieved a 2.6 fold throughput increase for receivers with $N_{RA} = 4$, up to eight tags colliding in one slot and one acknowledged tag out of them. In [8], we proposed a channel estimation method with a modified tag response. This modification requires small changes on the tag and changes in the standards. The proposed method provides excellent results in comparison to perfect channel knowledge in scenarios when all tags involved in a collision have a different "postpreamble". Moreover, we showed that with the receiver that can recover from collisions of up to eight tags colliding in one slot and acknowledge two tags, the expected throughput is even 5.033 times higher, compared to the throughput of a conventional reader.

In this work, we study the theoretical throughput of the FSA systems and its associated constraints. We investigate the influence of the receiver structure and the channel estimation process on the throughput. Furthermore, we propose a channel estimation technique which can provide better collision recovery and analyse its performances by means of simulations.

The rest of the paper is organized as follows: The state of the art is briefly described in the following Section II. The analysis of constraints and performance increase of the throughput of FSA systems with the capability of recovering from collisions on the physical layer and acknowledging all tags involved in collisions is presented in Section III.

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In Section IV the proposed collision recovery method with successive interference cancellation and projection of the constellation into the orthogonal subspace of the interference is explained. The analysis of the performance is conducted in Section V and the last section finally concludes the paper.

Table I
TERMS AND PARAMETERS

Variable	Description
N_{RA}	number of receiving antennas
$M = 2N_{RA}$	collision recovery factor / number of tags the reader is capable to resolve
$R \in [0..N]$	number of tags transmitting in the same slot
$j \in [1..R]$	tag index per slot for $R > 0$
$i \in [1..N_{RA}]$	antenna index
$\mathbf{s}_c(t)$	received signal vector $\in \mathbb{C}^{N_{RA} \times 1}$
$\mathbf{H_c}$	channel matrix $\in \mathbb{C}^{N_{RA} \times R}$
$\mathbf{a}(t)$	modulation vector $\in \mathbb{R}^{R \times 1}$
N	number of tags within the reader range
F	number of slots in a frame
J	number of tags the reader acknowledges

II. RFID MULTI ANTENNA SYSTEM

If it is assumed that the transmit and receive part of a reader are perfectly isolated (there is no carrier leakage), the received signal can be written as:

$$\mathbf{s_c}(t) = \mathbf{H_c}\mathbf{a}(t) + \mathbf{n}(t). \tag{1}$$

Here, $\mathbf{H_c}$ represents the $N_{\mathrm{RA}} \times R$ channel matrix with channel coefficients $h_{i,j}$. The channel coefficient $h_{i,j}$ represents the channel between reader, the j^{th} tag and the i^{th} receive antenna and is modelled as the multiplication of a forward channel $h_j{}^f$ and a backward channel $h_{i,j}{}^b$ as explained in [7]. Additionally, $\mathbf{a}(t)$ is the $R \times 1$ modulation vector with the elements $a_j(t)$; $\mathbf{s_c}(t)$ and $\mathbf{n}(t)$ are the $N_{\mathrm{RA}} \times 1$ column vectors with the elements $s_{\mathrm{c},i}(t)$ and $n_i(t)$, of the received signal and noise, respectively. For convenience, Table I gives an overview of the most important parameters and terms used in this paper. Small bold terms indicate vectors, capital indicate matrices.

From Equation (1), we can observe that all signals, except the modulation signal of a tag, are complex values. Considering that, we can split Equation (1) in real and imaginary parts and as a result, the number of equations is doubled, and therefore, the separation of up to $M = 2N_{\mathrm{RA}}$ tags is feasible and M is a collision recovery factor. Now, the channel matrix and the received signals have the form: $\mathbf{H} = \left[\Re\{\mathbf{H_c}\} \;\; \Im\{\mathbf{H_c}\}\right]^T$, $\mathbf{s}(t) = \left[\Re\{\mathbf{s_c}(t)\} \;\; \Im\{\mathbf{s_c}(t)\}\right]^T$, where $\Re\{\cdot\}$ selects the real part and $\Im\{\cdot\}$ selects the imaginary part of the argument.

In order to resolve collision using multiple receive antennas, an MMSE receiver is proposed in [7] and the output signal of the receiver is:

$$\hat{\mathbf{a}}_{\mathrm{MMSE}}(t) = \left(\hat{\mathbf{H}}^H\hat{\mathbf{H}} + \sigma^2\mathbf{I}_R\right)^{-1}\hat{\mathbf{H}}^H \cdot \left(\mathbf{s}(t) - \hat{\mathbf{H}}\bar{\mathbf{a}}(t)\right), \tag{2}$$

where $\hat{\mathbf{H}}$ is the estimated channel matrix and $\hat{\mathbf{H}}^H$ denotes its Hermitian transpose. Furthermore, $\bar{\mathbf{a}}(t) = E\{\mathbf{a}(t)\} = \frac{1}{2}$ due to the on-off keying modulation, σ^2 is the noise power, and $\mathbf{I}_R$ denotes the $R \times R$ identity matrix.

A tag response to the *Query* command, according to the EPCglobal standard for UHF RFID [1], consists of a preamble (identical for all tags involved in a collision) and a 16 bit-random number (RN16) and such response is not suitable for channel estimation in collision scenarios. Hence, in [8], we proposed the modification of a tag response by adding a “postpreamble”. In order to fulfil the channel estimation requirements, our “postpreamble” is designed to be different for each tag, and mutually orthogonal as explained in [8], [9].

For channel estimation, we use a Least Squares (LS) estimator [10]:

$$\hat{\mathbf{H}}_{\mathrm{LS}} = \mathbf{s}_{\mathrm{pp}}(t) \cdot \mathbf{S}_{\mathrm{M}}^{H}\left(\mathbf{S}_{\mathrm{M}}\mathbf{S}_{\mathrm{M}}^{H}\right)^{-1}, \tag{3}$$

where $\mathbf{S}_{\mathrm{M}}$ denotes the set of the M “postpreambles” and $\mathbf{s}_{\mathrm{pp}}(t)$ is the part of the received signal containing the “postpreamble”. A perfect knowledge of the “postpreamble” set, as well as that all tags involved in collision have a unique “postpreamble”, were assumed in the simulations conducted in [8].

III. THROUGHPUT OF THE FSA WITH CR

In this work, we focus on FSA, as defined in the second-generation EPCglobal standard for passive UHF RFID [1]. According to the standard, the reader announces the frame start with the *Query* command. All tags that are in the tag population covered by the reader are choosing slots for transmission. If more tags are active in a slot, a collision occurs and the entire slot is discarded. By the use of the readers with CR, it is possible to use the information from the collision slots and to increase the throughput. In order to find theoretical boundaries for performance evaluation of the collision recovery, we are analysing receiver structure and channel estimation constraints on the system throughput.

A. Throughput constrained with receiver structure

Based on our receiver structure, we are able to recover from collisions of $R \leq M = 2N_{RA}$ tags. Here, we are taking into account our current state of the art receiver structure ($N_{RA} = 4$) with a collision recovery factor $M = 8$. If we assume that we have perfect channel knowledge, we can resolve collisions of $R \leq M$ tags and acknowledge all tags ($J = R$) participating in it, the theoretical maximum can be calculated according to:

$$T = \sum_{R=1}^{M}\binom{N}{R}\left(\frac{1}{F}\right)^R\left(1 - \frac{1}{F}\right)^{N-R}R. \tag{4}$$

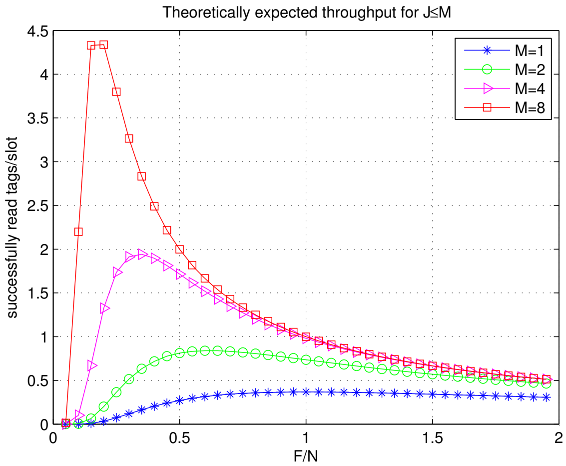

Figure 1. Expected throughput as a function of slots per tag population F/N for $J \leq M = 2N_{RA}$ acknowledgements

In Table II values of the maximal theoretical throughput and the optimal frame size normalized to the tag population size are shown together with the relative improvement to the throughput of a conventional system. Here, the maximal theoretical throughput is 4.479 and is achieved for the frame size 0.173. These results are obtained for the MMSE receiver with perfect channel knowledge.

Table II
OPTIMAL RATIO F_{opt}/N AND MAXIMAL THEORETICAL THROUGHPUT

System	F_{opt}/N	Exp. Throughput	Rel. Imp.
$M=1 \quad J=1$	1	0.368	1.000
$M=2 \quad J\leq 2$	0.618	0.841	2.285
$M=4 \quad J\leq 4$	0.339	1.944	5.283
$M=8 \quad J\leq 8$	0.173	4.479	12.171

Still, for the MMSE receiver (Equation (2)), we need to have the channel estimate $\hat{\mathbf{H}}$. In [8] we have modified the tag response to the *Query* command by adding a "postpreamble" in order to perform channel estimation. The desired case is that all tags, that are participating in a collision, have orthogonal "postpreambles". Thus, an additional constrain to this maximum is the channel estimation with the "postpreambles" set. Based on that, we can distinguish several possible scenarios.

B. Collision scenarios

We envision a set of eight mutually orthogonal "postpreambles" (explained in [8]) and for easier understanding, for each "postpreamble" sequence, there is a corresponding colour as shown in Figure 2.

If there are five tags transmitting in one slot, the following scenarios are possible:

Scenario 1: All tags involved in a collision have different/unique colours (different mutually orthogonal "postpreambles"). The probability of this scenario is:

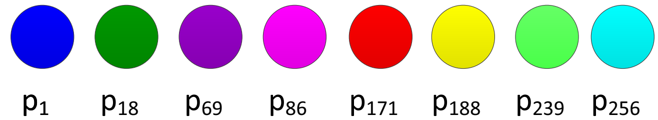

Figure 2. Set of "postpreambles" / colours

$$P_{1+1+1+1+1} = \frac{8 \cdot 7 \cdot 6 \cdot 5 \cdot 4}{8^5} = 0.2051. \tag{5}$$

Scenario 2: Two out of five active tags have the same colour while the other three are different, with probability:

$$P_{2+1+1+1} = \frac{\binom{5}{2} \cdot 8 \cdot 7 \cdot 6 \cdot 5}{8^5} = 0.5127. \tag{6}$$

Scenario 3: Just one tag is having a distinct colour, the other four tags can be categorized in two groups of two tags each with the same colour. The probability of this scenario is:

$$P_{2+2+1} = \frac{\binom{5}{2} \cdot \binom{3}{2} \cdot 8 \cdot 7 \cdot 6}{8^5} \cdot \frac{1}{2} = 0.1538. \tag{7}$$

Scenario 4: Two tags are having unique colours, while the other three are using the same colour:

$$P_{3+1+1} = \frac{\binom{5}{3} \cdot 8 \cdot 7 \cdot 6}{8^5} = 0.1025. \tag{8}$$

Scenario 5: Three tags are using the same colour while two tags are using an identical but different colour.

$$P_{3+2} = \frac{\binom{5}{3} \cdot \binom{2}{2} \cdot 8 \cdot 7}{8^5} = 0.0171. \tag{9}$$

Scenario 6: Only one tag has a distinct colour, the other four are identical.

$$P_{4+1} = \frac{\binom{5}{4} \cdot 8 \cdot 7}{8^5} = 0.0085. \tag{10}$$

Scenario 7: All tags involved in the collision are using the same colour.

$$P_{5} = \frac{\binom{5}{5} \cdot 8}{8^5} = 0.000242. \tag{11}$$

All scenarios for five tags transmitting in one slot are shown in Figure 3. In Table III the probabilities of Scenario 1 and Scenario 2 are illustrated for up to eight tags transmitting in one slot. The last column of Table III lists the sum of probabilities for both scenarios. As long as the number of tags per slot is small to moderate, the majority of the cases is covered.

Note that in Equation (4) we assumed to be capable of resolving all R tags in each slot. Now taking into account our current receiver capability of resolving only Scenarios 1 and 2, we have to modify the throughput:

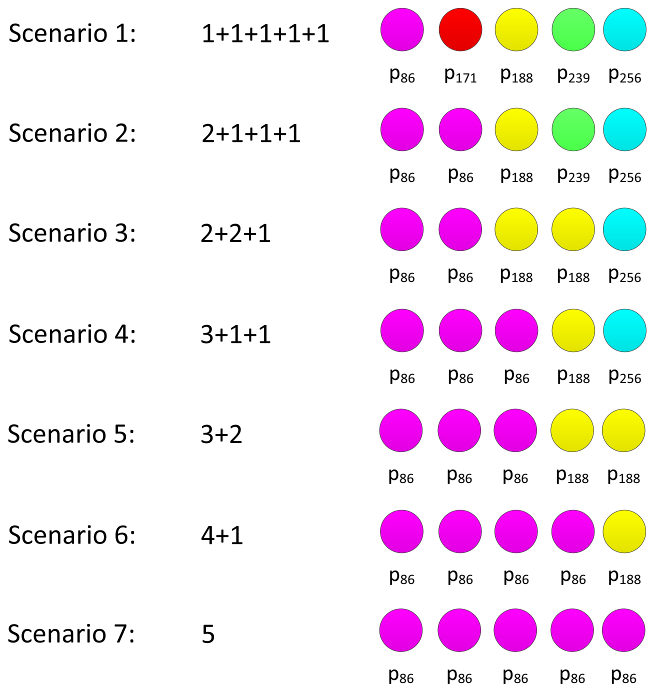

Figure 3. Possible scenarios with $R = 5$ tags

Table III
PROBABILITIES OF SCENARIOS FOR UP TO EIGHT TAGS.

$R \backslash P_s(R)$	Scen. 1	Scen. 2	$\sum$ Prob.
$R = 1$	$P_1 = 1$		1
$R = 2$	$P_{1+1} = 0.875$	$P_2 = 0.125$	1
$R = 3$	$P_{1+1+1} = 0.656$	$P_{2+1} = 0.328$	0.984
$R = 4$	$P_{1+..+1} = 0.410$	$P_{2+1+1} = 0.492$	0.902
$R = 5$	$P_{1+..+1} = 0.205$	$P_{2+..+1} = 0.513$	0.718
$R = 6$	$P_{1+..+1} = 0.077$	$P_{2+..+1} = 0.385$	0.462
$R = 7$	$P_{1+..+1} = 0.019$	$P_{2+..+1} = 0.202$	0.221
$R = 8$	$P_{1+..+1} = 0.002$	$P_{2+..+1} = 0.067$	0.069

$$T^{s1,s2} = \sum_{R=1}^{M} \binom{N}{R} \left(\frac{1}{F}\right)^{R} \left(1 - \frac{1}{F}\right)^{N-R} R \cdot \cdot \left(P_{s1}(R)\frac{R_{s1}^{sol}}{R} + P_{s2}(R)\frac{R_{s2}^{sol}}{R}\right). \quad (12)$$

Here, the probability of each scenario is taken into account together with the number of tags that can be resolved. Assuming that our advanced receiver can estimate the channels accurately enough to recover from these collisions ($R_{s1}^{sol} = R$ and $R_{s1}^{sol} = R$), the throughput is constrained just with the probabilities $P_{s1}(R)$ and $P_{s2}(R)$, that Scenario 1 or Scenario 2 can be resolved. Comparing with Figure 2, we now obtain the more realistic Figure 4.

Comparing Table II and Table IV, we observe that for the receivers with collision recovery factor $M = 1$ and $M = 2$, the values for the maximal theoretical throughput as well as the optimal frame size are the same. This is due to the fact that with Scenario 1 and Scenario 2 we have covered all possible scenarios. For higher values of M this is different. For example, in the case of a receiver with collision recovery factor $M = 4$, the throughput is calculated as:

$$T_{M=4}^{s1,s2} = T_{R=1}^{s1,s2} + T_{R=2}^{s1,s2} + T_{R=3}^{s1,s2} + T_{R=4}^{s1,s2}. \quad (13)$$

The difference is in the last two terms because for the case of $R = 3$ tags transmitting in one slot, we do not cover all possible scenarios but 98.4%; while in the case of $R = 4$, we cover a bit above 90%. For the receivers with a higher collision recovery factor, the difference between throughputs is increasing because the percentage of uncovered scenarios is much higher. For example, for the case when we have $R = 8$ tags transmitting with Scenario 1 and Scenario 2, we can cover less than 7% of all possible scenarios.

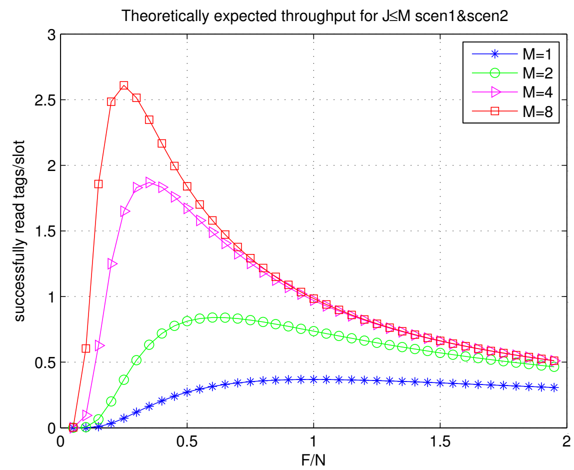

Figure 4. Expected throughput as a function of slots per tag population F/N for $J \leq M = 2N_{RA}$ acknowledgements in Scenario 1 and 2

Table IV
OPTIMAL RATIO F_{opt}/N AND MAXIMAL THEORETICAL THROUGHPUT JUST IN SCENARIO 1 AND 2

System	F_{opt}/N	Exp. Throughput	Rel. Imp.
$M = 1 \quad J = 1$	1	0.368	1.000
$M = 2 \quad J \leq 2$	0.618	0.841	2.285
$M = 4 \quad J \leq 4$	0.346	1.870	5.082
$M = 8 \quad J \leq 8$	0.245	2.610	7.092

IV. COLLISION RECOVERY

When $R = 4$ tags are active in the same slot and received by $N_{RA} = 2$ antennas, a part of a signal in vector form with "postpreambles" will be as below:

$$\begin{bmatrix} \mathbf{s}_1^{pp}(t) \\ \mathbf{s}_2^{pp}(t) \end{bmatrix} = \begin{bmatrix} h_{1,1} & h_{1,2} & h_{1,3} & h_{1,4} \\ h_{2,1} & h_{2,2} & h_{2,3} & h_{2,4} \end{bmatrix} \begin{bmatrix} \mathbf{p}_a \\ \mathbf{p}_b \\ \mathbf{p}_c \\ \mathbf{p}_c \end{bmatrix} + \begin{bmatrix} \mathbf{n}_1(t) \\ \mathbf{n}_2(t) \end{bmatrix} \quad (14)$$

Here, Tag 1 and Tag 2, included in a collision, are using mutually orthogonal "postprambles", $\mathbf{p_a}$, $\mathbf{p_b}$, while the remaining Tag 3 and Tag 4 are having the same "postpreamble", $\mathbf{p_c}$, which is Scenario 2. In this situation, we cannot use the channel estimation technique from [8] because the tags involved in collisions do not have unique and mutually orthogonal "postpreambles". Hence, we propose a collision recovery method with a successive interference cancellation (SIC) and a projection of the constellation into the orthogonal subspace of the interference.

A. Successive interference cancellation - SIC

We use successive interference cancellation - [11] to take out the signals from the tags with unique colours. We assume that colliding tags are perfectly synchronized. First, we estimate the channel based on the part of the received signal with "postpreambles" and the set of "postpreambles" $\mathbf{S}_{\mathrm{M}}$. We use a Least Squares (LS) estimator:

$$\hat{\mathbf{H}} = \mathbf{s}_{\mathrm{pp}}(t) \cdot \mathbf{S}_{\mathrm{M}}^{H}(\mathbf{S}_{\mathrm{M}}\mathbf{S}_{\mathrm{M}}^{H})^{-1}. \tag{15}$$

After obtaining the channel estimation, we select the strongest tag signal. The strongest tag signal corresponds to the strongest channel coefficient found as the maximum of $\left\|\hat{\mathbf{H}}\right\|_F^2$, where $\|\cdot\|_F^2$ denotes the Frobenius norm. In this search, we ignore the signals from tags with the same "postpreambles". Furthermore, with an MMSE receiver, we extract $\mathbf{a}(t)$:

$$\hat{\mathbf{a}}_{\mathrm{MMSE}}(t) = \left(\hat{\mathbf{H}}^H\hat{\mathbf{H}} + \sigma^2\mathbf{I}_R\right)^{-1}\hat{\mathbf{H}}^H \cdot \left(\mathbf{s}(t) - \hat{\mathbf{H}}\bar{\mathbf{a}}(t)\right). \tag{16}$$

Later on, we remodulate the signal from the strongest tag and subtract it from the received signal:

$$\bar{s}_{\mathrm{i}}(t) \leftarrow \bar{s}_{\mathrm{i}}(t) - \hat{h}_{ij}\hat{a}_j(t). \tag{17}$$

Here, j denotes the signal from the strongest tag and i represents the index of the receive antenna. In vector form:

$$\bar{\mathbf{s}}(t) \leftarrow \bar{\mathbf{s}}(t) - \hat{\mathbf{h}}_{\mathbf{j}}\hat{a}_j(t), \tag{18}$$

and $\hat{\mathbf{h}}_{\mathbf{j}} = [\hat{h}_{1j}, .., \hat{h}_{ij}, .., \hat{h}_{\mathrm{N_{RA}}j}]^T$ is the column vector of channel coefficients between reader, strongest tag j and receiving antennas $i = 1..N_{RA}$. In this way, we have cleaned the received signal from the influence of the strongest tag and that signal is used as the input signal for the next iteration, together with the set of "postpreambles" without the "postpreamble" of the strongest tag. In each iteration, as an output, we obtain the signal from the strongest tag and we store those channel coefficients that correspond to that tag.

B. Channel estimation with projections

Theoretically, we should be able to differentiate $2^{R=2} = 4$ states in the IQ diagram, since the signal after SIC consists of the signals originating from two tags. According to the EPCglobal standard for UHF RFID [1], a tag response to the *Query* command begins with a defined preamble. Thus, during such preamble, all tags modulate the same bits and we can estimate the state when tags are reflecting:

$$\hat{C}_i^{r,r} = \max\left\{s_i\left[k\right]\right\}_{t_{1bit}}, \tag{19}$$

where $s_i\left[k\right]$ is the sample of the received signal from antenna i taken within duration of the first preamble bit t_{1bit}.

The preamble consists just of bits 1 and 0 and during its duration, tags are moving between states $\hat{C}_i^{r,r}$ and $\hat{C}_i^{a,a}$ (subspace C_S). State $\hat{C}_i^{a,a} = E\left\{s_i\left[k\right]\right\}_T$ is determined as the average value of the received signal over time period T before the tag response. After the preamble, a "postpreamble" and an RN16 are transmitted, and the realization of remaining states happens when tags modulate different data. This states are estimated as the points with the maximal signal strength in the subspace $C_{S\perp}$ orthogonal to C_S [6]:

$$\hat{C}_i^{a,r} = \max_k\left\{s_{i\perp}\left[k\right]\right\}, \quad \hat{C}_i^{r,a} = \min_k\left\{s_{i\perp}\left[k\right]\right\}, \tag{20}$$

and $s_{i\perp}\left[k\right]$ is the signal component located in the subspace $C_{S\perp}$.

Since the modulation signals are on-off keying, the channel coefficients are:

$$\hat{h}_{i,1} = \hat{C}_i^{r,r} - \hat{C}_i^{a,r}, \quad \hat{h}_{i,2} = \hat{C}_i^{r,r} - \hat{C}_i^{r,a}, \tag{21}$$

With this, we have completed the channel estimation procedure and with the use of an MMSE receiver from Equation (2) we extract the tag signals. In general, the signal that remains after SIC is formed of signals from tags with the same "postpreambles" which are disturbed with the channel, noise and errors accumulated through SIC. Due to this disturbances and errors, this states sometimes cannot be determined correctly.

V. Performance Analysis

The performance of the proposed collision recovery is analysed through MATLAB simulations. As a performance measure of the receiver, we observe the Bit Error Ratio (BER) and the average number of successfully received packets (NSRP) per slot for different levels of average Signal-to-Noise Ratios (SNR). The SNR has been averaged over the receiving antennas and calculated as explained in [7]. To evaluate the quality of the simulations, the confidence interval that contains 95% of the obtained results is plotted around each point in the BER figures. As one packet is considered the part of a tag signal that contains the RN16 number. The NSRP is calculated as the number of packets in a slot that are received without errors. This number is averaged over $N_{\mathrm{iter}} = 50 \cdot 10^{\frac{\mathrm{SNR}[dB]}{10}} + 50$ iterations. The simulated RFID reader has one transmitting and four receiving antennas (N_{RA}) and the number of tags transmitting in the same slot (R) is varied from one, transmission without collision, up to eight tags. The channel is modelled as a double Rayleigh fading channel and individual Rayleigh

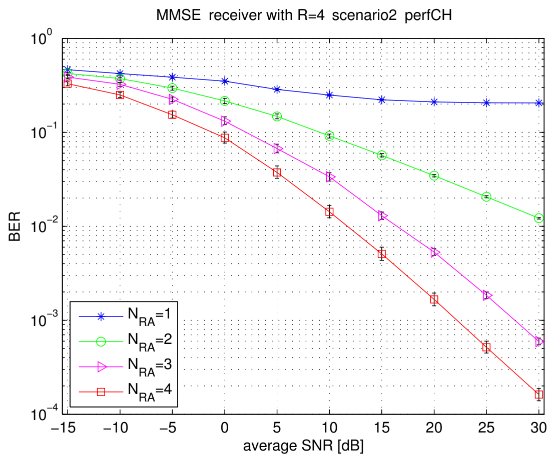

Figure 5. BER vs. SNR for MMSE rec. ($R = 4$, perf.ch LS:2+1+1).

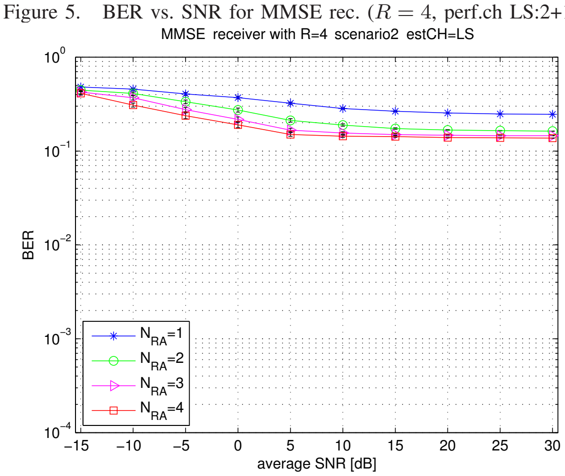

Figure 6. BER vs. SNR for MMSE rec. ($R = 4$, est.ch LS:2+1+1).

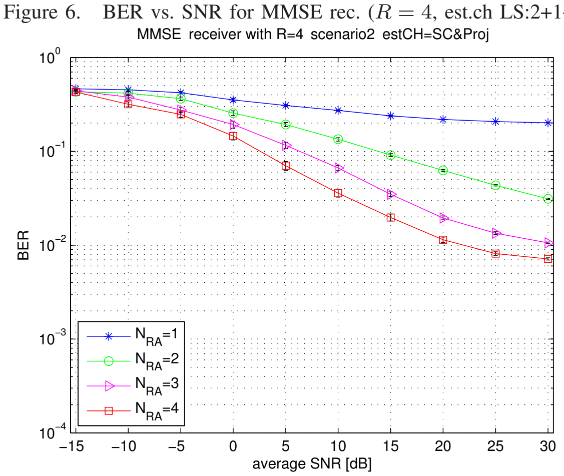

Figure 7. BER vs. SNR for MMSE rec. ($R = 4$, est.ch SIC Proj:2+1+1).

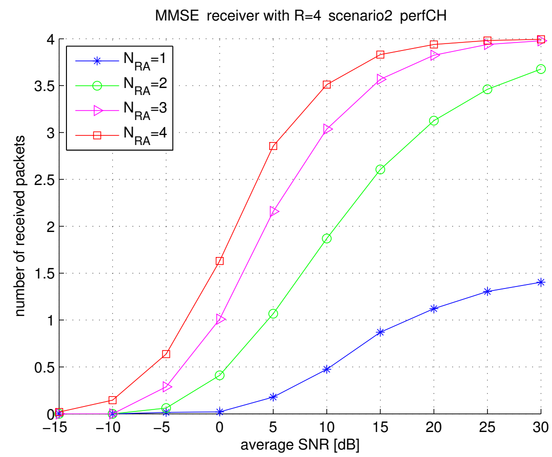

Figure 8. NSRP vs. SNR for MMSE rec. ($R = 4$, perf. ch:2+1+1).

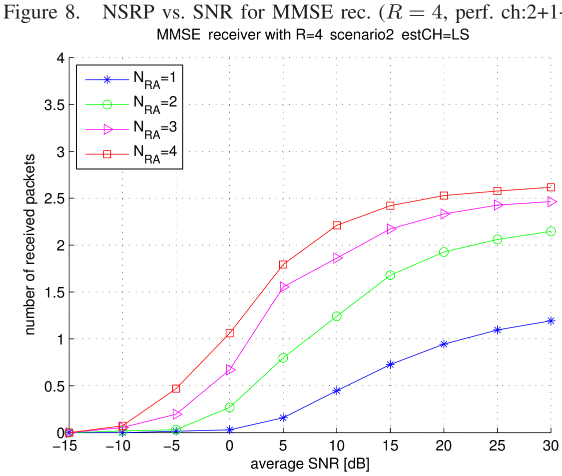

Figure 9. NSRP vs. SNR for MMSE rec. ($R = 4$, est.ch SC Proj:2+1+1).

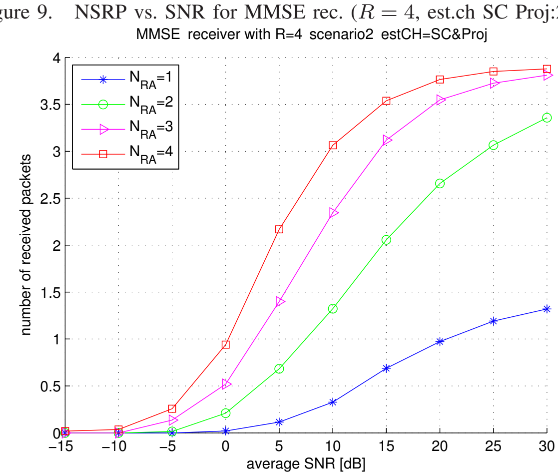

Figure 10. NSRP vs. SNR for MMSE rec. ($R = 4$, est.ch SC Proj:2+1+1).

channel coefficients are independent zero mean circularly symmetric complex Gaussian random variables as in [6].

In Figures 5-10, the obtained results for the MMSE receiver with different types of channel knowledge in the case of four tags ($R = 4$) transmitting in one slot are shown. Figure 5 shows the BER of the receiver with perfect channel knowledge. With the perfect knowledge of the channel coefficients, the "postpreamble" distribution does not have any influence on performance, as expected. In Figure 8, the average NSRP per slot for different number of receiving antennas on the reader is presented. In the case of four tags transmitting in the same slot with two receive antennas, we can on average successfully receive more than 3.6 packets at $\overline{\mathrm{SNR}} = 30\mathrm{dB}$. These two graphs will serve as an indicator of the highest achievable performance of the designed system.

Figures 6 and 9 present results in the case of regular LS channel estimation. Since here, two out of four tags are using the same sequence, the channel cannot be estimated properly and the MMSE receiver cannot resolve collisions. The BER curves are saturated at high error values and it seems that all packets are affected with errors. However, average NSRP values show that with the receiver that has more than one receive antenna, we can on average receive correctly more than two packets. This is due to the fact that errors are mostly in packets from tags with the same "postpreambles" while the packets from other two tags are less affected with errors during the channel estimation process.

The performance of the RFID reader with proposed collision recovery through successive interference cancellation and projection of the constellation into the orthogonal subspace of the interference are shown in Figures 7 and 10. We observe that by using the proposed method with two receive antennas, the collision of four tags is resolvable, performances are comparable to the results obtained with perfect channel knowledge and on average we receive more than 3.4 packets. However, by increasing the number of receiving antennas on the reader side, the BER curves are not following the trend of the reader with perfect channel knowledge. This is due to the fact that we cannot increase the performance with this method after we exceed the necessary number of receiving antennas $N_{_{RA}} = \frac{M}{2}$.

A comparative overview of the expected throughput for the MMSE receiver with different number of receiving antennas in case of up to eight tags transmitting in one slot is given in Figure 11. The throughput of that system is:

$$T^{s1,s2}_{\mathrm{FSA,i}} = \sum_{R=1}^{M} Pr_{_R} \cdot \left\{ Sr^{s1}_{i,R} \cdot P_{s1} + Sr^{s2}_{i,R} \cdot P_{s2} \right\}. \tag{22}$$

Here, $Pr_{_R}$ represents the probability that exactly R tags are transmitting in one slot and it is calculated as:

$$Pr_{_R} = \binom{N}{R} \left(\frac{1}{F_{\mathrm{opt}}}\right)^R \left(1 - \frac{1}{F_{\mathrm{opt}}}\right)^{N-R}, \tag{23}$$

and F_{opt} is taken from Table IV. Additionally, $Sr^{s1}_{i,R}$ and $Sr^{s2}_{i,R}$ represent the success rate of a system with i receive antennas in Scenario 1 and Scenario 2, respectively. Since, we take into account all colliding tags and we try to acknowledge all of them ($J = R$), the success rate of a system represents the average number of successfully received packets, NSRP. Furthermore, P_{s1} denotes the probability that Scenario 1 occurs and P_{s2} is the probability of Scenario 2, both taken from Table III.

In the case of perfect channel knowledge, "postpreamble" scenarios are irrelevant and the throughput is calculated as:

$$T_{\mathrm{FSA,i}} = \sum_{R=1}^{M} Pr_{_R} \cdot Sr_{_{i,R}}, \tag{24}$$

where the probability that exactly R tags are transmitting in one slot is calculated according to Equation (23) with the F_{opt} taken from Table II.

In Figure 11, the maxima of the theoretically expected throughput, from Table II, in the case when we can recover from all collision scenarios are indicated with solid horizontal lines. Dotted horizontal lines represent maxima of the theoretically expected throughput, from Table IV, when just Scenario 1 and Scenario 2 are resolvable. The receivers with perfect channel knowledge are represented with solid lines while the receivers with the proposed collision recovery are represented with dotted lines. It can be observed that a group of curves are approaching their theoretical limits. For the SNR of 30 dB, the throughput of a system with collision recovery factor $M = 8$ in the case of perfect channel knowledge, all scenarios resolved, is 4.431. That is more than 12 times higher than a throughput of a conventional system which is represented with the red curve (−⊖−) and can just work with singleton slots. For the same SNR and the same collision recovery factor, the throughput of a proposed collision recovery method is 2.548, i.e., almost seven times the throughput of a conventional system. This improvements are in accordance with the theoretically calculated relative improvements from Table II and Table IV.

VI. Conclusion

In this paper, we have analysed the theoretical throughput of FSA RFID systems with collision recovery. For a reader capable of successfully reading and acknowledging up to eight tags per slot is achievable to have a throughput increase of more than 12 times the throughput of a conventional RFID reader. This theoretical throughput is only achievable in the case of perfect channel knowledge. On the other hand, for collision recovery, our receivers need channel estimation and if we include the probability of the scenarios for which we are able to estimate channel, the maximal theoretical throughput is seven times the throughput of a conventional system. Furthermore, we have proposed a collision recovery procedure for recovering from collision in which two of colliding tags have the same "postpreamble",

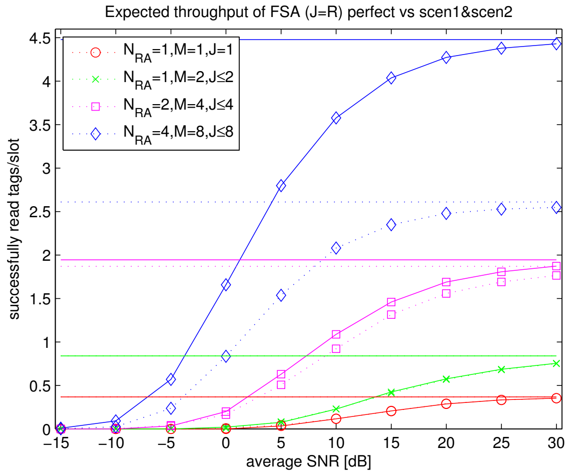

Figure 11. Throughput in the case of perfect channel knowledge vs. throughput in case of "postpreambles" (scenario 1 and 2)

part of a signal used for channel estimation. In our proposed method, we first perform successive interference cancellation during which we take out the signals of tags with unique "postpreamble". After that, the signal composed of tags with the same "postpreamble" is remained. This collision we are resolving with the projection of the constellation into the orthogonal subspace of the interference. The obtained results show that our proposed method provides satisfactory results and the throughput is approaching to corresponding theoretical maximum. Our next step is to investigate the influence of tag synchronization to our proposed collision recovery. Moreover, we are going to find a procedure for collision recovery in the case of other scenarios and to look at the adaptation of the protocol in order to acknowledge all tags in a slot.

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