RFID Reader with Multi Antenna Physical Layer Collision Recovery Receivers

Jelena Kaitovic, Robert Langwieser, Markus Rupp
Institute of Telecommunications, Vienna University of Technology, Austria
Email: {jelena.kaitovic, robert.langwieser, markus.rupp}@tuwien.ac.at

***Abstract*—Radio Frequency Identification (RFID) is a wireless identification technology which often operates in environments with multiple RFID tags. Already introduced multiple antenna receivers can recover from a collision of up to *M* tags as long as *M* is less than the number of receive antennas and the channel is known at the receiver. This paper proposes a Zero-Forcing (ZF) and a Minimum Mean Square Error (MMSE) receiver which allows the separation of up to *M=2N_R* tags, where N_R is the number of receiving antennas on the reader. The proposed algorithms are verified through simulations.**

I. INTRODUCTION

Usually several Radio Frequency Identification (RFID) tags are operating within the coverage area of an RFID reader. Tag responses are scheduled on the Medium Access Control (MAC) layer using Framed Slotted Aloha (FSA). Only slots with a single tag response can be decoded successfully. If multiple tags respond simultaneously, a collision at the air interface occurs, and the information is discarded [1].

Slots with colliding RFID tag signals were investigated in the following papers: Khasgiwale et al. [2] estimated the number of tags involved in collision by information from tag collisions on the physical layer. In that way they have achieved a more accurate estimation of the RFID tag population. They also showed that it is possible to recover from collisions and correctly read the data of the colliding tags. Shen et al. [3] analysed the signal constellations of responses from colliding tags. The authors proposed an algorithm for recovery from tag collisions. Furthermore, they simulated the error performance when multiple colliding tags were present. Yu et al. [4] used beamforming in combination with anti-collision techniques. They have separated the tag population into sectors and used FSA or binary tree search in each sector. The authors have not tried to recover from collisions. Mindikoglu et al. [5] developed a blind signal separation receiver for RFID collision recovery with multiple antennas based on the zero constant modulus algorithm. Finally, Angerer et al. [6] showed an increase of the theoretical throughput of FSA RFID systems with physical layer collision recovery receivers. They have observed that single antenna receivers are only capable of recovering from collisions of two tags and that multiple antenna receivers can recover from a collision of up to M tags if M is less than the number of receiving antennas and the channel is known at the receiver. This paper follows the work of Angerer et al. and represents its extension to more receiving antenna readers which can separate up to R tags, transmitting in the same slot, as long as $R \leq M = 2N_R$, where N_R is the number of receiving antennas on the reader.

The rest of the paper is organized as follows: Section II. describes the channel model of this work. The collision resolving receivers are presented in Section III. The theoretical increase in performance of an FSA system with the capability of recovering from collision at the physical layer is discussed in Section IV. In Section V. performances are shown in simulations and discussed, and the last section finally concludes the paper.

II. CHANNEL MODEL

A channel h with the presence of a mean or line of sight (LOS) component $E\{h\} = \bar{h}$ and a fading component h_w can be described as a Ricean channel [7]. A MIMO channel in the presence of Ricean fading can be modelled as a summation of a mean component of the channel and a fading component of the channel. Here, K in (1) represents the Ricean factor of the channel. A channel with pure Rayleigh fading is obtained with $K = 0$, while a link without fading is described for $K \to \infty$.

$$h = \sqrt{\frac{K}{1+K}}\bar{h} + \sqrt{\frac{1}{1+K}}h_w. \tag{1}$$

As shown in (2) every channel coefficient $h_{i,j}$ is modelled as the multiplication of a forward channel ${h_j}^f$ and a backward channel ${h_{i,j}}^b$.

$$h_{i,j} = {h_j}^f {h_{i,j}}^b, \tag{2}$$

where the index i represents antenna i and j denotes tag j.

As an example, the channel matrix between the reader, two tags and four receiving antennas is shown in (3).

$$\mathbf{H_c} = \begin{bmatrix} h_{1,1} & h_{1,2} \\ h_{2,1} & h_{2,2} \\ h_{3,1} & h_{3,2} \\ h_{4,1} & h_{4,2} \end{bmatrix}. \tag{3}$$

The coefficients described above are illustrated in Figure 1.

III. COLLISION RESOLVING RECEIVERS

In this paper Zero Forcing (ZF) and Minimum Mean Square Error (MMSE) receivers are discussed. The received signal can be written as:

$$\mathbf{s_c}(t) = \mathbf{H_c}\mathbf{a}(t) + \mathbf{I} + \mathbf{n}(t), \tag{4}$$

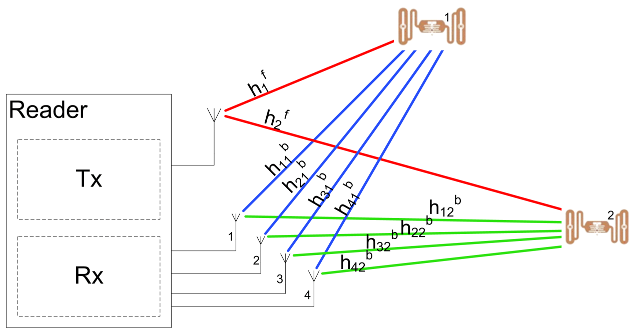

Fig. 1. Channel model with four receiving antennas and two tags.

where $\mathbf{H_c}$ denotes the $N_R \times R$ channel matrix and $\mathbf{a}(t)$ is the $R \times 1$ modulation vector with the elements $a_j(t)$. Furthermore, $\mathbf{s_c}(t)$, $\mathbf{I}$, $\mathbf{n}(t)$ are the $N_R \times 1$ column vectors of the received signal, the carrier leakage and noise, respectively.

Using the fact that $a_j(t)$, the modulation signal of tag j, is real valued, the received signal, presented by (4), can be equivalently reformulated to:

$$\begin{bmatrix} \Re\{\mathbf{s_c}(t)\} \\ \Im\{\mathbf{s_c}(t)\} \end{bmatrix} = \begin{bmatrix} \Re\{\mathbf{H_c}\} \\ \Im\{\mathbf{H_c}\} \end{bmatrix} \mathbf{a}(t) + \begin{bmatrix} \Re\{\mathbf{I}\} \\ \Im\{\mathbf{I}\} \end{bmatrix} + \begin{bmatrix} \Re\{\mathbf{n}(t)\} \\ \Im\{\mathbf{n}(t)\} \end{bmatrix}, \quad (5)$$

where $\Re\{\cdot\}$ selects the real part and $\Im\{\cdot\}$ selects the imaginary part of the argument. In this way the number of equations is doubled. It allows the separation of up to M=$2N_R$ tags.

In the following equations for the ZF and the MMSE receivers the channel matrix and the received signal have the form of:

$$\mathbf{H} = \begin{bmatrix} \Re\{\mathbf{H_c}\} \\ \Im\{\mathbf{H_c}\} \end{bmatrix}, \quad (6)$$

$$\mathbf{s}(t) = \begin{bmatrix} \Re\{\mathbf{s_c}(t)\} \\ \Im\{\mathbf{s_c}(t)\} \end{bmatrix}. \quad (7)$$

In order to simplify equations the carrier leakage is set to zero.

A. Zero Forcing Receiver - ZF

The Zero Forcing receiver inverts the channel and eliminates inter-symbol interference (ISI), but at the expense of noise enhancement [7]. The ZF receiver is described by:

$$\mathbf{r}_{\mathrm{ZF}}(t) = \left(\hat{\mathbf{H}}^H \hat{\mathbf{H}}\right)^{-1} \hat{\mathbf{H}}^H \left(\mathbf{s}(t) - \hat{\mathbf{H}}\bar{\mathbf{a}}(t)\right), \quad (8)$$

where $\hat{\mathbf{H}}$ is the matrix of the estimated channel, $\hat{\mathbf{H}}^H$ denotes its Hermitian transpose, $\bar{\mathbf{a}}(t) = E\{\mathbf{a}(t)\}$ and $\mathbf{r}_{\mathrm{ZF}}$ is the signal at the output of the ZF receiver.

B. Minimum Mean Square Error Receiver - MMSE

A more sophisticated approach is an MMSE receiver that offers a balance between noise enhancement and ISI mitigation [7]. The MMSE filter is described by:

$$\mathbf{G}_{\mathrm{MMSE}} = \left(\hat{\mathbf{H}}^H \hat{\mathbf{H}} + \sigma^2 \mathbf{I}_R\right)^{-1} \hat{\mathbf{H}}^H, \quad (9)$$

where σ denotes noise variance, and $\mathbf{I_R}$ is the $R \times R$ identity matrix. The signal at the output of the MMSE receiver is obtained by:

$$\mathbf{r}_{\mathrm{MMSE}}(t) = \mathbf{G}_{\mathrm{MMSE}} \cdot \left(\mathbf{s}(t) - \hat{\mathbf{H}}\bar{\mathbf{a}}(t)\right). \quad (10)$$

IV. Framed Slotted Aloha - FSA

Framed Slotted Aloha is used for scheduling the transmission of tags. The EPCglobal standard for UHF RFID [8] applies FSA. In FSA systems, the reader starts a frame with F slots. The tags randomly select one of these slots for transmission. The tags send a 16 bit random number. When the tag receives a correct acknowledge, the arbitration process is finished and the tag returns its unique identifier. It is possible that some slots are not used by tags for transmission (empty slots), some are used by one tag (singleton slots) or it may occur that certain slots are used by several tags (collision slots), causing a collision. The expected number of slots with exactly R tags transmitting is given by [9]:

$$E\{\mu_R\} = F \binom{N}{R} \left(\frac{1}{F}\right)^R \left(1 - \frac{1}{F}\right)^{N-R}, \quad (11)$$

where μ_R is a random variable indicating the number of slots with exactly R tags transmitting, $E\{\cdot\}$ denotes the expected value and N represents the number of tags within the reader range.

The reader is capable of recovering from collision with $R \leq M$ tags transmitting in the same slot. If more than M tags collide, the slot is unreadable. The reader chooses one of these R tags and acknowledges this single tag ($J = 1$) while the other tag's responses are discarded. For this scenario, the throughput can be computed directly from (11).

$$T = \sum_{R=1}^{M} E\{\mu_R\} = \sum_{R=1}^{M} \binom{N}{R} \left(\frac{1}{F}\right)^R \left(1 - \frac{1}{F}\right)^{N-R}. \quad (12)$$

The frame size F can be optimized in order to maximize the average throughput. In Fig. 2 the expected throughput curves of receivers which are capable of recovering from collision of up to M tags are shown for a tag population of $N = 1\,000$. The expected throughput increases with M and converges toward one successful readout per slot for $M \to \infty$. In Table I the optimal values of frame size and average throughput are shown. The values are related to the tag population size for the reader which is capable of recovering from a collision of $M = \{1, 2, 4, 8\}$ tags and acknowledge one tag ($J = 1$).

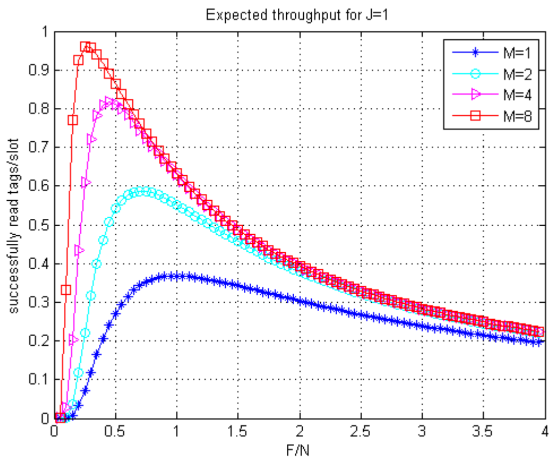

Fig. 2. Expected throughput for $J = 1$ in respect to frame size to tag ratio F/N.

V. PERFORMANCE SIMULATIONS

The performance of the proposed method for collision recovery is verified through MATLAB simulations. In order to compare the performances the Bit Error Ratio (BER) is computed by Monte Carlo simulations of slots with a varying number of tag responses. The simulated system consists of an RFID reader with four receiving antennas and the number of responding tags changes from one tag and transmission without collision to up to eight tags. In order to simplify the comparison, a channel matrix that follows a Rayleigh fading is assumed. The single Rayleigh channel coefficients are independent zero mean circularly symmetric complex Gaussian random variables with normalised energy $E\{|h_j|^2\} = 1$, which implies that the two tags participating in the collision experience the same path loss [6]. The average signal to noise ratio is calculated as:

$$\overline{\text{SNR}} \triangleq \frac{1}{N_R}\sum_i E\left\{\frac{|h_{i,j}|^2 {a_j}^2}{N_0}\right\}. \tag{13}$$

The simulation is run for different sets of input parameters, and for every set the channel parameters are calculated again. It is assumed that we have perfect channel knowledge.

As shown in the figures (Fig.3 - Fig.5) the ZF receiver is capable of recovering from collisions of the number of tags that is two times higher than the number of antennas. If two tags are active in the same slot, a collision occurs. A ZF receiver with one receiving antenna can resolve this collision.

TABLE I
OPTIMAL FRAME SIZE F_{opt} AND EXPECTED THROUGHPUT FOR READERS RESOLVING $M = \{1, 2, 4, 8\}$ COLLISIONS AND $J = 1$

M	F_{opt}/N	expected throughput	relative improvement
1	1	0.368	1.000
2	0.707	0.587	1.595
4	0.452	0.817	2.220
8	0.265	0.962	2.614

The obtained results are also verified through comparison with [6] (in Fig.3, black dotted line with diamonds). Straightforward results are observed in case of four active tags and eight active tags. It is shown that a ZF receiver with two receiving antennas can resolve collisions of four tags. In the case of eight colliding tags four receiving antennas on the reader are necessary to recover from this collision. Similar results are obtained with MMSE receivers and the simulation results are illustrated in the figures (Fig.6 - Fig.8). Around each point in the graphs confidence intervals of 95 % have been plotted (magnified on Fig.3). These intervals contain 95% of the obtained results.

In the figures (Fig.9 - Fig.11) the number of successfully received packets is shown with respect to signal to noise ratio and different numbers of receiving antennas at the reader.

The number of successfully received packets is calculated in the following way: Received packets are compared with transmitted packets. If an error in transmission has occurred, the number of packets with errors is incremented. That has been done for every received packet in one slot. The total number of packets with errors is subtracted from the total number of packets sent in the respected slot and in that way the number of successfully received packets is obtained. The same steps are conducted in every slot. At the end, the total number of successfully received packets is divided by the number of slots which correspond to that value of SNR (given with (14)):

$$N_{\text{slots}} = 50 \cdot 10^{\frac{\text{SNR}[dB]}{10}} + 50. \tag{14}$$

If two tags are active in the same slot, a reader with one receiving antenna is able to successfully receive more than 1.6 packets on average for the simulated SNR ratio. Furthermore, it can be observed that for a higher number of receiving antennas, looking at the same SNR, the number of successfully received packets increases much faster. It can easily be shown that with a higher SNR, the reader can successfully receive two packets. Similar results are obtained for four and eight tags, transmitting in the same slot.

In Fig.15 the expected throughput for ZF and MMSE receivers is shown with different numbers of receiving antennas at the reader and in case of up to eight tags transmitting in the same slot. The four dashed horizontal lines indicate the maximum of the theoretically expected throughput of receivers which are capable of recovering from collision of up to one tag ($M = 1, J = 1$), two tags ($M = 2, J = 1$), four tags ($M = 4, J = 1$) and eight tags ($M = 8, J = 1$), respectively.

The receiver can only decode one of the colliding packets ($J = 1$), which is chosen to be the packet with the strongest received signal. The expected throughput is calculated in the following way: The received packet (extracted from the strongest signal) is compared with the transmitted packet. If an error in the transmission has occurred, the number of packets with errors is increased. The same steps are repeated in every slot. At the end, the total number of packets with errors is divided by the number of slots (different for every value of SNR) and subtracted from one. In this way the success rate of the simulated system is achieved.

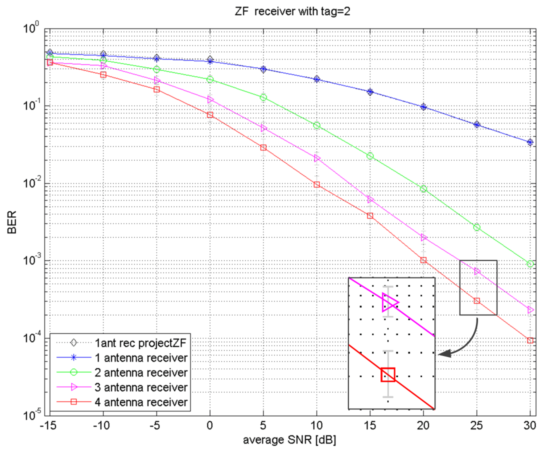

Fig. 3. BER vs SNR for ZF receiver with two tags.

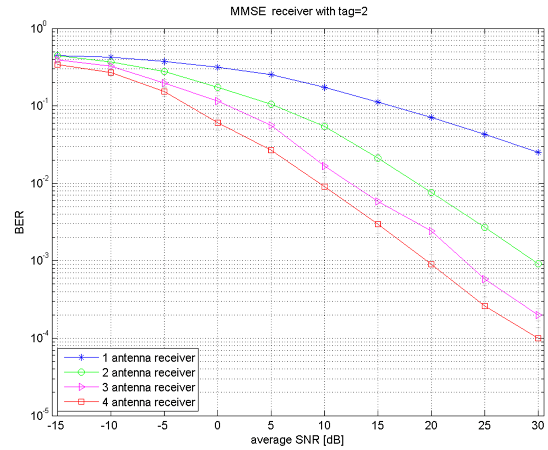

Fig. 6. BER vs SNR for MMSE receiver with two tags.

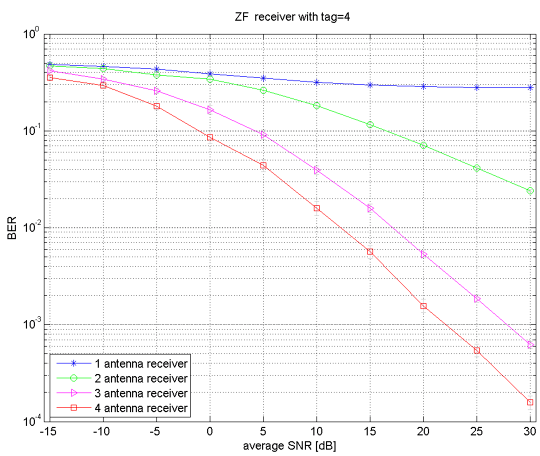

Fig. 4. BER vs SNR for ZF receiver with four tags.

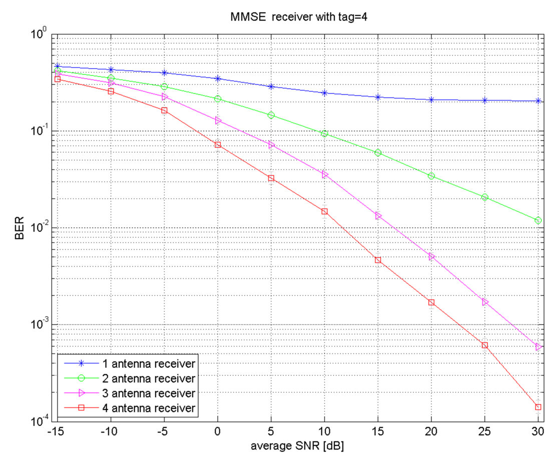

Fig. 7. BER vs SNR for MMSE receiver with four tags.

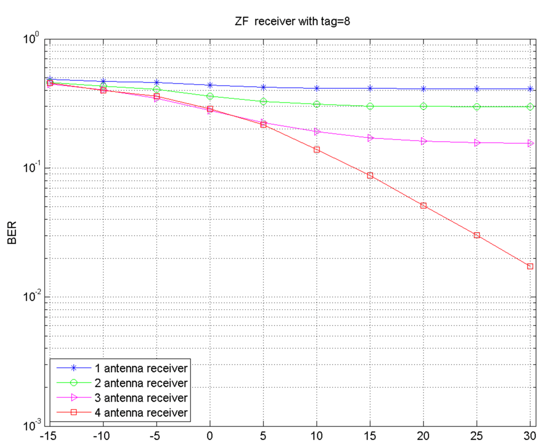

Fig. 5. BER vs SNR for ZF receiver with eight tags.

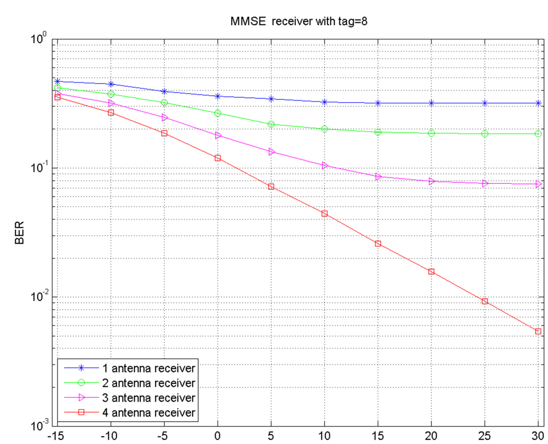

Fig. 8. BER vs SNR for MMSE receiver with eight tags.

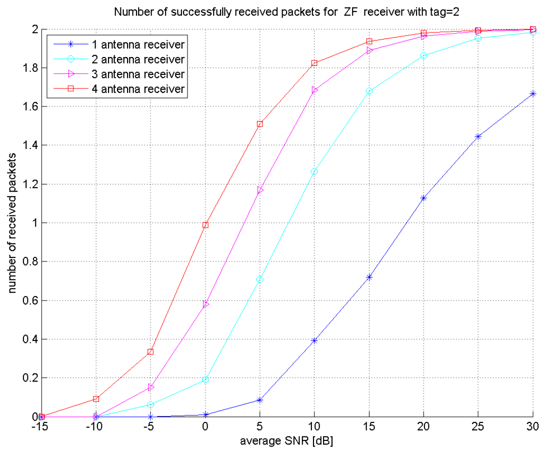

Fig. 9. Number of successfully received packets for ZF receiver and two tags.

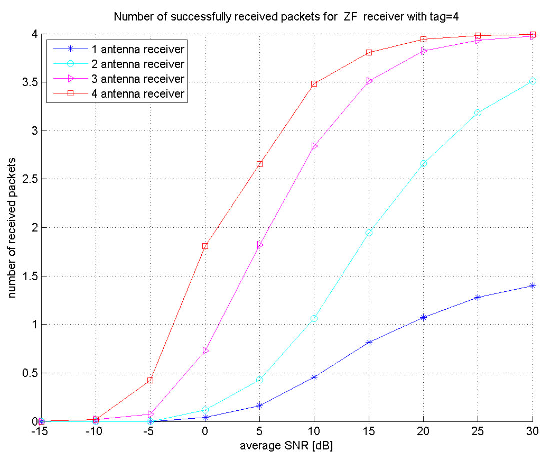

Fig. 10. Number of successfully received packets for ZF receiver and four tags.

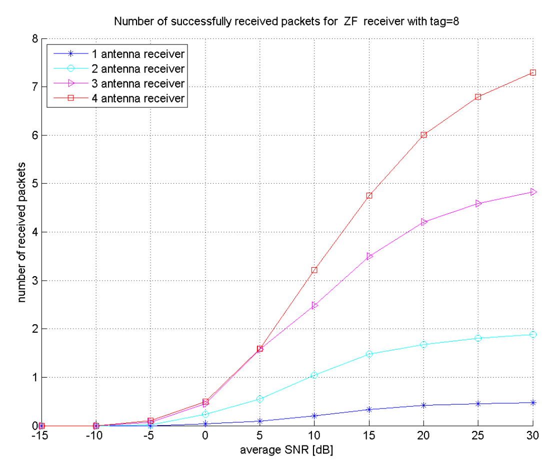

Fig. 11. Number of successfully received packets for ZF receiver and eight tags.

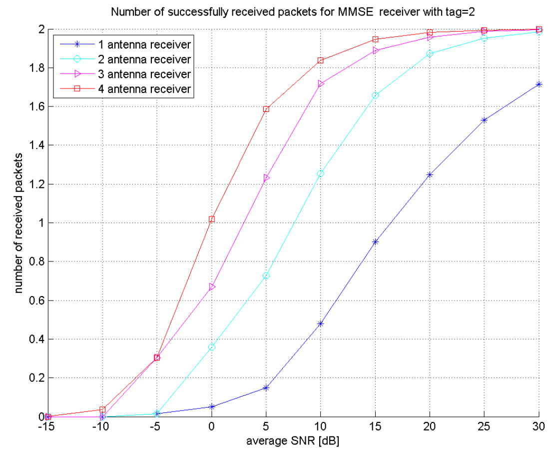

Fig. 12. Number of successfully received packets for MMSE receiver and two tags.

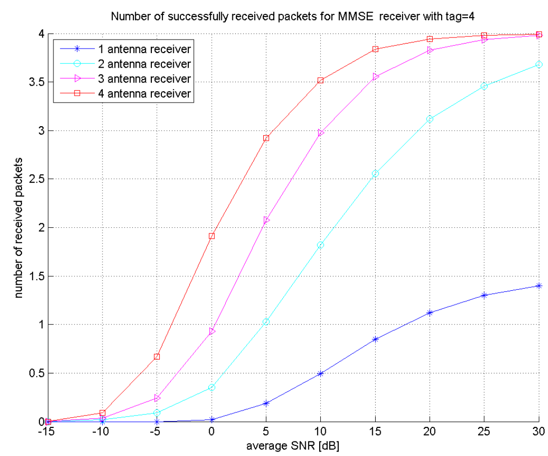

Fig. 13. Number of successfully received packets for MMSE receiver and four tags.

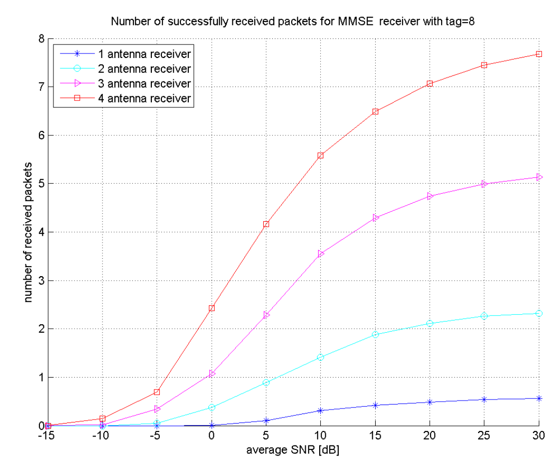

Fig. 14. Number of successfully received packets for MMSE receiver and eight tags.

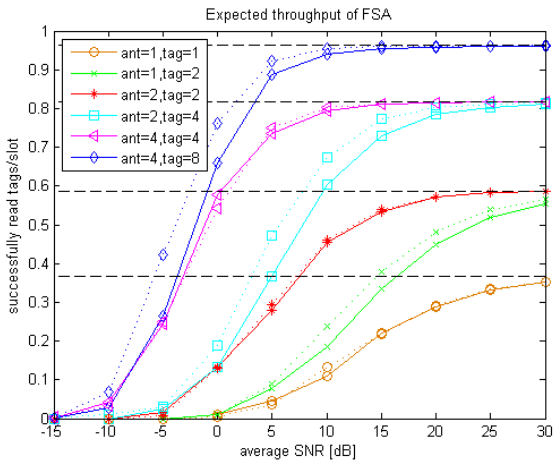

Fig. 15. Expected throughput of FSA scheme for ZF (solid lines) and MMSE (dotted lines) receivers.

The expected throughput is:

$$T_{\mathrm{FSA}} = \sum_{R=1}^{M} Pr_R \cdot Sr_{\mathrm{ant}=i,R}, \tag{15}$$

where Pr_R represents the probability that exactly R tags, of the total number of tags N, are transmitted in one slot, and $Sr_{\mathrm{ant}=i,R}$ is the success rate of the system with i receiving antennas at the reader if R tags are active in the same slot.

For the simulated SNR throughput curves are approaching the theoretical limit, and it can be observed that with the increase of SNR the curves will saturate. The orange lines in Fig.15 represent a conventional system with one antenna on the reader and one tag transmitting. The relative improvement shown in Table I can be compared with this curve.

VI. Conclusions

In this paper, it is shown that with the proposed design of RFID reader it is possible to recover from collisions that have a number of tags two times higher than the number of receiving antennas. The channel model for two receiving antennas and two tags, already proposed in [6], is extended to a more general case.

Simulation results for the ZF and the MMSE receivers, which are able to resolve collisions of up to eight tags, are presented. The throughput increase of FSA RFID systems with physical layer collision recovery receivers is identified. For a receiver capable of successfully reading and acknowledging one tag of a slot with up to eight tags, a throughput increase of approximately 2.6 times the throughput of a conventional RFID reader is achieved.

Acknowledgement

This work has been funded by the Christian Doppler Laboratory for Wireless Technologies for Sustainable Mobility, and its industrial partner Infineon Technologies. The financial support by the Federal Ministry of Economy, Family and Youth and the National Foundation for Research, Technology and Development is gratefully acknowledged.

References

[1] M. V. Bueno-Delgado, J. Vales-Alonso, and F. J. Gonzalez-Castao, “Analysis of DFSA anti-collision protocols in passive RFID environments,” in *Proc. 35th Conf. IEEE Industrial Electronics Society (IECON)*, Nov. 2009.

[2] R. S. Khasgiwale, R. U. Adyanthaya, and D. W. Engels, “Extracting Information from Tag Collisions,” in *Proc. of the IEEE International Conference on RFID*, Orlando, USA, April 2009.

[3] D. Shen, G. Woo, D. P. Reed, A. B. Lippman, and J. Wang, “Separation of Multiple Passive RFID Signals Using Software Defined Radio,” in *Proc. of the IEEE International Conference on RFID*, Orlando, USA, April 2009.

[4] J. Yu, K. H. Liu, X. Huang, and G. Yan, “An anti-collision algorithm based on smart antenna in RFID system,” in *Proc. of International Conference on Microwave and Millimeter Wave Technology, 2008. ICMMT 2008*, vol. 3, April 2008, pp. 1149–1152.

[5] A. F. Mindikoglu and A.-J. van der Veen, “Separation of overlapping RFID signals by antenna arrays,” in *IEEE International Conference on Acoustics, Speech and Signal Processing, ICASSP 2008*, April 2008, pp. 2737–2740.

[6] C. Angerer, R. Langwieser, and M. Rupp, “RFID Reader Receivers for Physical Layer Collision Recovery,” *IEEE Transactions on Communications*, vol. 58, no. 12, pp. 3526–3537, Dec. 2010.

[7] A. Paulraj, R. Nabar, and D. Gore, *Introduction to Space-Time Wireless Communication*. Cambridge University Press, 2003.

[8] EPCGlobal, “EPC Radio-Frequency Identity Protocols Class-1 Generation-2 UHF RFID,” [Online]. Available: http://www.epcglobalinc.org.

[9] C. Angerer, G. Maier, M. V. Bueno-Delgado, M. Rupp, and J. Vales-Alonso, “Single Antenna Physical Layer Collision Recovery Receivers for RFID Readers,” in *Proc. of the IEEE International Conference on Industrial Technology*, March 2010, pp. 1386–1391.