Single Antenna Physical Layer Collision Recovery Receivers for RFID Readers

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***Abstract*—Radio Frequency Identification (RFID) systems often are operated in environments with multiple RFID tags. In such an environment, a conventional RFID system resolves collisions of multiple tags on the medium access control layer, discarding the signals of the physical layer. This paper proposes a zero-forcing and an interference cancellation receiver architecture for an RFID reader, to recover from collisions of two tags on a physical layer and identify tags successfully even in case of a collision. The expected throughput increase is approximately 1.6 times the throughput of a conventional reader. We explore the signal properties of collisions and propose a model for the physical layer. Moreover, we present a method for estimating the signal constellation states in a collision. The entire structure, including channel estimation and both of the proposed receivers are verified with data generated during a measurement. Additionally, performance simulations of the two structures with different channels are shown.**

I. Introduction

Radio Frequency Identification (RFID) is a wireless identification technology. Depending on the power supply of RFID tags, we distinguish between active and passive RFID. Passive RFID tags do not carry any battery for power supply but receive the energy they need for processing from a carrier wave provided by the RFID reader. For communication, passive RFID tags utilise a backscatter technology. Additionally, RFID is operated in various frequency bands. This work focuses on passive RFID in the Ultra High Frequency (UHF, 866-950 MHz) band. Furthermore, we stick to the EPCglobal standard for passive UHF RFID [1].

If several RFID tags are within the coverage area of an RFID reader, Framed Slotted Aloha (FSA) is applied as a medium access scheme. Such a system resolves collisions on the Medium Access Control layer (MAC). In case of multiple tags answering simultaneously, a collision at the air interface occurs, and the information of the physical layer is discarded [2].

However, recently different groups started to pay attention on slots with colliding RFID tag signals: Khasgiwale et. al. [3] utilise information from tag collisions on the physical layer to estimate the number of tags involved in that specific collision. This information enhances the accuracy of RFID tag population estimators. Furthermore, the authors point out the potential to recover from collisions and correctly read the tags of the collisions, however they do not show any receiver capable of solving this problem. Shen et. al. [4] rigorously analyse signal constellations of colliding tag responses. In contrast to our work, they focus on Low Frequency (LF) tags. Their model is supported by measurement data, and they propose a recovery algorithm for tag collisions. Additionally, they simulate the error performance in case of multiple colliding tags. The potential of improving arbitration on the MAC layer using interference cancellation receivers for general multiple access channel applications like WLAN or Bluetooth has also been identified by Halperin et. al. [5]. Yu et. al. [6] combine beamforming with anti collision techniques, separating the tag population into sectors and running FSA or binary tree search in each sector, but do not try to recover from collisions.

As a motivation for this work, Section II discusses the theoretical performance increase of an FSA system which is capable to recover from tag collisions. Section III accurately models tag collisions and signal constellations in RFID reader receivers. Based on that model, two receivers which are capable of recovering from tag collisions on the physical layer for passive UHF RFID systems are proposed in Section IV. Both, the model as well as the receivers are corroborated with measurement data. Section VI compares the performance of the receivers in simulation in various channels, while the last section provides a discussion and concludes the paper.

II. Framed Slotted Aloha with Collision Recovery

Framed slotted aloha is used to arbitrate the air interface and to schedule the transmission of a tag population of N tags. Thereby, the reader starts a frame with K slots, issuing a `QUERY` command, which announces the frame size K (slot $k \in [1, \ldots, K]$). The tags randomly select one of these following slots for transmission, which are indicated by `QUERY_REP` commands from the reader. It may occur that

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certain slots are not used by tags for transmission (empty slots), used by one tag (singleton slots) or more than one tag (collision slots), generating a collision at the air interface. The expected number of slots with exactly r tags transmitting is given by:

$$K\binom{N}{r}\left(\frac{1}{K}\right)^{r}\left(1-\frac{1}{K}\right)^{N-r}. \tag{1}$$

Conventional RFID readers only can read data in singleton slots, leading to the well known maximum average throughput of 0.37 successful readouts per slot. This throughput is achieved if the frame size is set equal to the tag population size ($K = N$).

However, if it is possible on the physical layer to recover from a slot with $r \leq M$ tags participating in a collision and to correctly read and acknowledge one of these tags, we only encounter an unreadable slot if more than M tags transmit in the same slot. Then the average throughput is given by:

$$\sum_{r=1}^{M}\binom{N}{r}\left(\frac{1}{K}\right)^{r}\left(1-\frac{1}{K}\right)^{N-r}. \tag{2}$$

In order to maximise the average throughput the optimal frame size, that is the number of slots K_{op} for the frame, can readily be derived by solving the following equation:

$$\sum_{r=1}^{M}\binom{N}{r}\left(\frac{1}{K_{op}}\right)^{r+1}\left(1-\frac{1}{K_{op}}\right)^{N-r-1}\left(\frac{N}{K_{op}}-r\right)r = 0.$$

Figure 1 shows the expected throughput of receivers being capable to recover from collisions with up to M tags depending on K/N. Compared to a conventional reader ($M = 1$), a reader that is able to recover from a collision with up to $M > 1$ tags adjusts a shorter frame size for maximal throughput. This result is intuitive, as a reader with e.g. $M = 2$ maximises the expected number of slots with a single ($r = 1$) and two responses ($r = 2$), while a conventional reader just maximises the expected number of singleton slots.

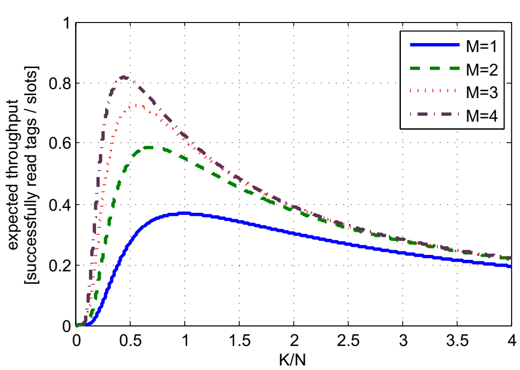

Fig. 1. Expected throughput depending on frame size K.

Similarly, the expected throughput increases with the parameter M, and converges toward 1 successfully read tag per slot for $M \to \infty$. The optimal values of frame sizes related to the tag population size and the average throughput is shown in Table I for $M = 1, \ldots, 4$. A reader with the capability of recovering from a collision with two tags ($M = 2$), already achieves a theoretical increase of the expected throughput of 1.6 times the throughput of a conventional reader, motivating the development of such a receiver. In the following section we develop a signal model for collisions with two tags, and propose a corresponding reader receiver architecture with $M = 2$ in Section IV.

M	K_{op}/N	average throughput
1	1	0.368
2	0.707	0.587
3	0.550	0.726
4	0.452	0.817

TABLE I
OPTIMAL FRAMESIZE K_{op} FOR READERS WITH $M = 1 \ldots 4$.

III. Signal Constellations in Tag Collisions

A. Signal Model of Collisions on the Channel

Figure 2 shows the basic communication between a tag and an RFID reader. In passive RFID systems, the reader provides energy to the tag in form of a continuous carrier transmission. While passive tags absorb energy from that field, this carrier transmission also leaks into the receiver of the RFID reader. This carrier leakage is:

$$s_{leak}(t) = A_{c,leak}\sin(\omega_c t + \varphi_{leak}). \tag{3}$$

Here $\omega_c = 2\pi f_c$, and f_c denotes the carrier frequency of the transmitted wave of the reader. The phase shift φ_{leak} results from the propagation delay between transmit and receive antennas, while the amplitude $A_{c,leak}$ of the leakage is determined by the decoupling between the transmitter and receiver, which is assumed not to depend on time during one transmission. For transmitting information to the reader, tags use backscatter modulation. Thereby each tag i change from absorbing energy (tag absorb state, S_a) to reflecting energy (tag reflect state, S_r), by mismatching their antenna input impedance. This backscattered signal is:

$$s_{tag\,i}(t) = a_i(t)\sin(\omega_c t); \quad i = 1, 2. \tag{4}$$

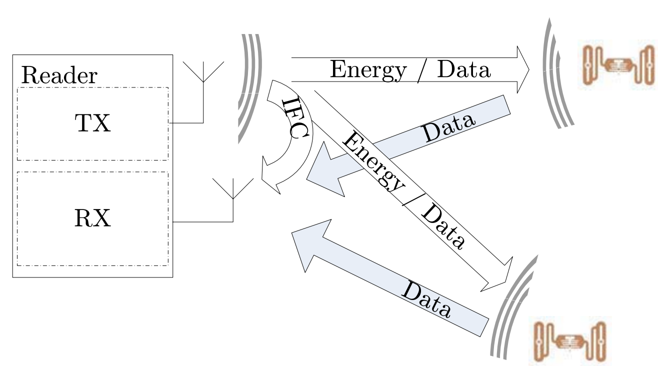

Fig. 2. Communication between reader and two tags.

The modulation signal $a_i(t)$ follows an on-off keying, and is assumed to have a rectangular shape with the backscatter link frequency being its fundamental frequency. At the air interface, the tag modulation adds up with the carrier leakage. Note that in a practical system, this carrier leakage can be up to 90dB stronger than the backscattered signal [7]. In case of a collision of two tags, these modulation sequences add up with the carrier leakage:

$$s_{RX}(t) = s_{leak}(t) + h_{c,1}a_1(t)\sin(\omega_c t + \varphi_1) + h_{c,2}a_2(t)\sin(\omega_c t + \varphi_2) + n(t). \quad (5)$$

The two-way channel reader-to-tag-to-reader adds the attenuation $h_{c,i}$ and inserts the phaseshift φ_i for each tag i. In our model we assume that the channel attenuation $h_{c,i}$ and phase shift φ_i do not change significantly during one transmission period. Further, if the tag does not realise perfect on-off keying ($a(t) \in [0,1]$) but introduces an additional attenuation and phase shift, these artifacts are included in the channel behaviour in our model.

B. Constellations in the Baseband of the Receiver

After receiving the collided signals at the antenna, the reader first downconverts the receive signal to the baseband, using I/Q demodulators. It is important to note, that all signal components are modulated to the same carrier frequency, which originates from a *single* source, namely the transmitter of the reader. This important property inherent in backscatter technology enables the downconversion of all signal components with the same modulation frequency. Hence, the complex baseband signal is:

$$s(t) = A_{leak} + h_1 a_1(t) + h_2 a_2(t) + n(t), \quad (6)$$

with $h_1 = h_{c,1}e^{j\varphi_1}$ and $h_2 = h_{c,2}e^{j\varphi_2}$ denoting the complex channel coefficients, $A_{leak} = A_{c,leak}e^{j\varphi_{leak}}$ denoting the complex carrier leakage and $n(t)$ denoting the noise. Stacking the real ($Re\{\cdot\}$) and imaginary ($Im\{\cdot\}$) part of each of the complex values into a vector, i.e. $\mathbf{s}(t) = [Re\{s(t)\}, Im\{s(t)\}]^T, \mathbf{h}_i = [Re\{h_i\}, Im\{h_i\}]^T, \mathbf{a}_{leak} = [Re\{A_{leak}\}, Im\{A_{leak}\}]^T, \mathbf{n}(t) = [Re\{n(t)\}, Im\{n(t)\}]^T$, we can rewrite Equation(6) to:

$$\mathbf{s}(t) = \mathbf{a}_{leak} + \mathbf{h}_1 a_1(t) + \mathbf{h}_2 a_2(t) + \mathbf{n}(t). \quad (7)$$

Figure 3 shows the constellation of two colliding tags in the baseband I/Q plane of the reader receiver: While both tags absorb energy, the reader only discovers the carrier leakage (absorb state of both tags, $S_{a,a} = A_{leak}$). If the tag 1 backscatters information to the reader, this modulation adds up with the carrier leakage and gives a second state in the I/Q plane, the tag 1 reflect state and tag 2 absorb state ($S_{r,a} = A_{leak} + h_1$). The vice-versa situation, where tag 1 absorbs energy while tag 2 reflects energy, realises the point $S_{a,r}(= A_{leak} + h_2)$, and finally, if both tags reflect energy simultaneously, the state $S_{r,r}(= A_{leak} + h_1 + h_2)$ is produced. In general, we find up to $2^{N_{coll}}$ different states, with N_{coll} indicating the number of tags participating in the collision. Hence, the number of different states generated in the I/Q plane indicates the number of tags participating in the collision [3], [4], which can be utilised to enhance tag population estimators (such as e.g. [8]).

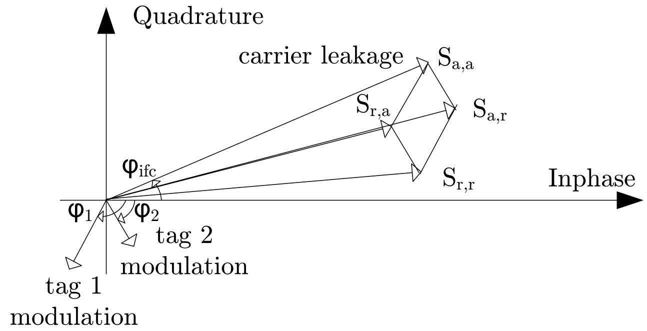

Fig. 3. Reader baseband I/Q diagram of collision of two tags.

Furthermore, by knowing the various states, we are able to define decision regions which jointly decode both sequences participating in the collision. The location of the constellation in the I/Q plane depends on the phase and amplitude of the carrier leakage and on the tag modulation signals. The phase and amplitude of the carrier leakage are basically determined by the decoupling and delay between transmitter and receiver. The tag modulation phase and amplitude depend on the reader-to-tag distance, the tag modulation behaviour and the (fading) channel. In general, the various states of the constellation in the I/Q plane of the receiver is unknown and arbitrary to the reader receiver.

As tags switch between their absorb and reflect state according to a rectangular modulation function with the basic frequency defined as the backscatter link frequency [1], a matched filtering is realised by an integration over one such period. This changes the pulse shape of the tag modulation signal from rectangular to triangular. Hence, the signal moves between the states indicated in Figure 3. Instead of the matched filter, Khasgiwale et. al. [3] only apply a low pass filter cutting at the fifth harmonic of the backscatter link frequency for delimiting the noise bandwidth.

Furthermore, in UHF RFID the various tag modulation signals $a_i(t)$ are not synchronous: on the one hand they may respond with a deviation from a nominal backscatter link frequency (symbol frequency offset), and on the other hand they may start modulating with a small timing offset, as defined by the standard [1]. While two synchronous tags only move on straight trajectories between the various states in Figure 3 (as this is the case in the example of Figure 4), non synchronous tags move basically within the entire area between the four states in Figure 3.

IV. Collision Resolving Receivers

With the above developed model in mind, we are now ready to develop two different receiver structures capable of recovering from collisions with at most two tags. As both

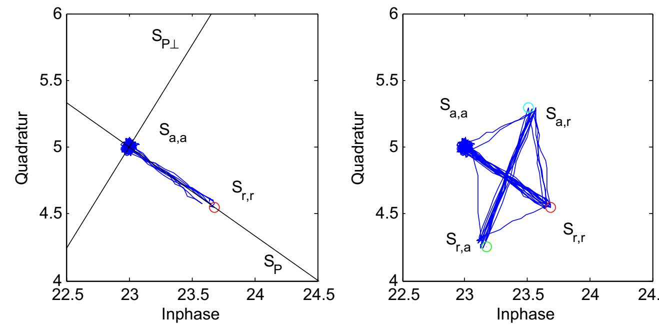

Fig. 4. Channel estimation: constellation during preamble and entire RN16 transmission.

receivers require channel knowledge, a channel estimation technique is proposed first.

A. Channel Estimation

Reviewing Equation (6), we find the two tag signals of interest, degraded with the carrier leakage and noise. While the tag signals are only active during times of backscatter modulation, the carrier is always leaking into the receiver. With the assumption that the carrier leakage is not changing significantly during one transmission from the tag to the reader, we can first estimate this leakage during times where both tags are in their absorb state ($S_{a,a}$). Such a period is defined by the EPCglobal standard by UHF RFID (and similarly by others) immediately before the tags respond (defined as T_1). In a digital receiver we can utilise this period to estimate the carrier interference ($A_{leak} = S_{a,a}$) and the noise power σ_n^2 as the temporal mean and variance during that interval T_1 [9], [10]:

$$\hat{S}_{a,a} = E\{s[k]\}_{T_1}, \tag{8}$$

$$\hat{\sigma}_n^2 = E\{|s[k]|^2\}_{T_1} - |E\{s[k]\}|^2_{T_1}. \tag{9}$$

$E\{\cdot\}_{T_1}$ denotes the averaged value over time period T_1, and k is the sample index.

Tag sequences start with a defined preamble. Hence, all tags modulate the same bits at the beginning. During the first bit of the preamble (t_{1bit}) we therefore can estimate the state $S_{r,r}$, which is determined at the largest deviation from $S_{a,a}$ in the I/Q plane:

$$\hat{S}_{r,r} = \max\left\{|s[k] - \hat{S}_{a,a}|\right\}_{t_{1bit}}. \tag{10}$$

Note that during the preamble, the receive signal just moves between the two states $S_{a,a}$ and $S_{r,r}$, as shown in the first subplot of Figure 4.

Finally, the realisation of the remaining states $S_{a,r}$ and $S_{r,a}$ depends on the generated data (16 bit random numbers, RN16). If only one tag responded to the last `QUERY` command, the receive signal is composed of two states and lies in a one-dimensional subspace of the I/Q plane defined by the absorb and reflect state of that tag. However, if several tags generate a collision, we also find signal components in the orthogonal subspace ($S_{P\perp}$) of the preamble subspace (S_P). These two orthogonal subspaces are indicated by the lines in the first subplot of Figure 4. The states $S_{a,r}$ and $S_{r,a}$ are then estimated at the points with maximal signal strength in this orthogonal subspace component:

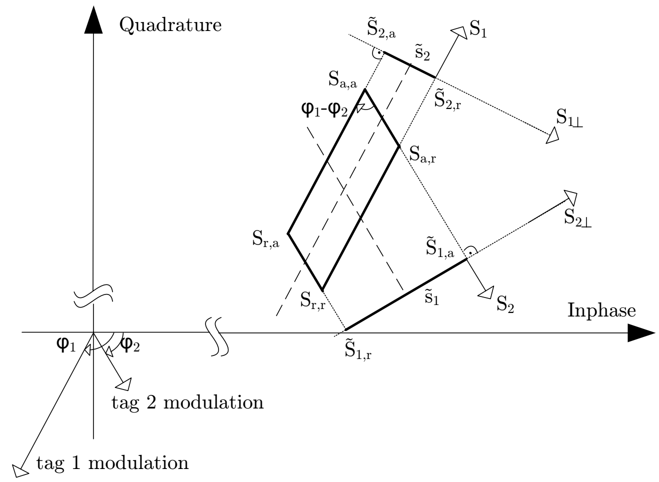

Fig. 5. Zero-forcing receiver with projection of the constellation into the orthogonal subspace to the interferer.

$$\hat{S}_{a,r} = \max\{s_\perp[k]\}, \;\; \hat{S}_{r,a} = \min\{s_\perp[k]\}. \tag{11}$$

Here, $s_\perp[k]$ denotes the signal component located in the orthogonal subspace ($S_{P\perp}$) of the space defined by the preamble (S_P). It is insignificant if we exchange $S_{a,r}$ and $S_{r,a}$ in our estimation, as it is irrelevant which decoded signal belongs to which tag. What we are interested in is only that we find two correctly decoded sequences.

As the modulation signals a_1 and a_2 are assumed to realise perfect on-off keying, the channel coefficients directly correspond to:

$$\hat{h}_1 = \hat{S}_{r,a} - \hat{S}_{a,a}, \;\; \hat{h}_2 = \hat{S}_{a,r} - \hat{S}_{a,a}. \tag{12}$$

B. Zero-Forcing Receiver

The first proposed receiver capable of resolving a collision with two tags participating, is a Zero-Forcing (ZF) receiver. It treats one of the two tag responses as interference, and projects the signal constellation into the subspace that completely cancels the interference, i.e. the subspace ($S_{i\perp}$) orthogonal to the interfering component (S_i, see Figure 5):

$$\tilde{\mathbf{s}}_1(t) = \left[\mathbf{I} - \frac{\mathbf{h}_2\mathbf{h}_2^T}{\mathbf{h}_2^T\mathbf{h}_2}\right]\mathbf{s}(t), \qquad \tilde{\mathbf{s}}_2(t) = \left[\mathbf{I} - \frac{\mathbf{h}_1\mathbf{h}_1^T}{\mathbf{h}_1^T\mathbf{h}_1}\right]\mathbf{s}(t). \tag{13}$$

Here $\mathbf{I}$ denotes the 2×2 identity matrix. The projected signals $\tilde{s}_i$ move between the projected states $\widetilde{S}_{i,a}$ and $\widetilde{S}_{i,r}$. The projection $\tilde{s}_i$ of each tag signal is thereafter synchronised and decoded separately (Figure 6).

We explicitly state that with this receiver it is only possible to recover from collision slots with two tags. In general we can not find a subspace in the two-dimensional I/Q plane which is orthogonal to more than one interferer, hence we can only

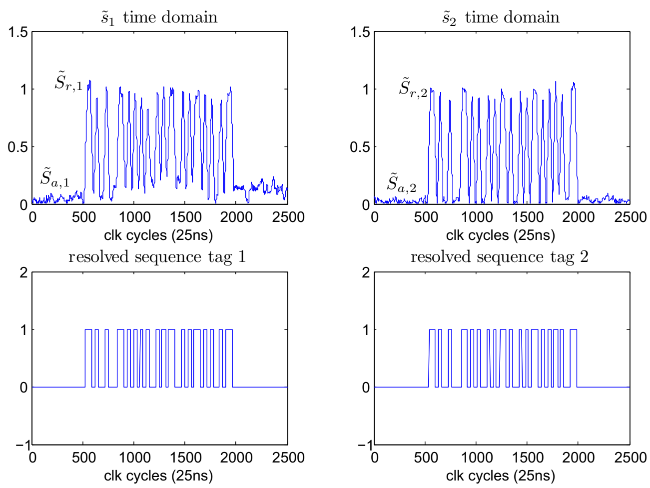

Fig. 6. Resolved collision with ZF receiver.

cancel one other tag in a collision slot with the proposed projection method.

The projection into the orthogonal subspace ($S_{i\perp}$) of the interfering signal (subspace S_i) also degrades the signal strength of the desired signal, and hence also the signal to noise ratio (SNR). The degradation depends on the angle between the two tag modulation signals and is proportional to $\sin(\varphi_1 - \varphi_2)$. Hence, if the two tag signals participating in the collision are close to orthogonal in the I/Q plane, the loss is small (the channel is well conditioned). However if the angles of the modulating signals are almost equal, a high fraction of receive signal power is lost by this projection (the channel is badly conditioned).

The zero-forcing receiver can also be interpreted as a receiver, setting two separate decision thresholds inside the area spanned by the four constellation points $S_{a,a}$, $S_{a,r}$, $S_{r,a}$ and $S_{r,r}$, as indicated by the dashed lines in Figure 5. Note that these decision regions are however different from those of a maximum likelihood receiver. For this kind of system deciding in the regions of the maximum likelihood receiver is infeasible, as the different tag signals do not show synchronous symbol timing.

C. Successive Interference Cancellation Receiver

Furthermore we propose a successive interference cancellation receiver, that is decoding the streams sequentially. First it selects the stream with higher receive signal power (reflected by h_i), which is first separated by the zero-forcing receiver as described above. After discriminating between '0' and '1', the result is remodulated and subtracted from the signal constellation. Assuming the decision process was correct, the interference for the second stream is canceled [11]. In a final step the remaining signal is sliced and decoded [9], [12]. This receiver exploits the fact, that the loss due to projection into the subspace just affects the signal that is decoded first.

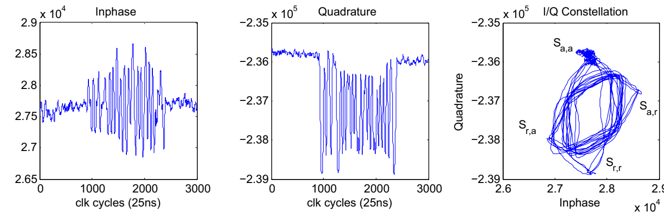

Fig. 7. Baseband signals of measurement data of collision with two tags.

V. Verification with Measurement Data

In order to verify both, our model of signal constellations of collisions, as well as the proposed receivers, we run our algorithms on measurement data of collisions with two commercially available tags. The measurement data was generated on our RFID prototyping environment [13], which is composed of a digital baseband processing part and analogue RF frontends. The measurement data was captured after an analogue-to-digital-converter (ADC) and imported into Matlab. Figure 7 shows the measurement data of the inphase and quadrature component in the time domain, as well as the I/Q constellation of the collision. Clearly, we can again determine the various states $S_{a,a}$, $S_{a,r}$, $S_{r,a}$ and $S_{r,r}$. As assumed in our model, the data samples are located within the area defined by those states. As the modulation signal of both tags is not synchronous, the receive signal moves on trajectories, that are not directly connecting the states, as mentioned in Section III.

We applied our proposed channel estimation algorithm, which correctly detects the appropriate states in the constellation of the measurement data. Furthermore, we applied both receiver structures, the zero-forcing receiver as well as the interference cancellation receiver. Figure 6 shows the resolved sequences of the example using the zero-forcing receiver: The first two subplots show the two projected signals into the orthogonal subspace of the interfering signal. The interference is completely canceled. The second two subplots show the separately sliced signals.

A major drawback of the result is, that it is not possible to verify that the resolved sequences are decoded correctly, as the transmitted data is not known (tags transmit a 16 bit random number). A justification for a correct functionality however is, that the decided signals are obviously two independent, correctly encoded FM0 sequences with a valid preamble, as we would expect them. Further, the following section provides simulation results, and clearly we can verify the functionality of the algorithms in simulation. The assumptions in the simulation and the previously proposed model are justified by the measurement data.

VI. Performance Simulations

We simulate the average Bit Error Ratio (BER) of the proposed Zero-Forcing (ZF) and ordered successive cancellation receivers (OSUC) in slots with two tags responding simultaneously (Figure 8), depending on E_b/N_0. The tag-to-reader channel [14] is modeled to be frequency flat and following a Rician or a Rayleigh fading distribution as proposed in

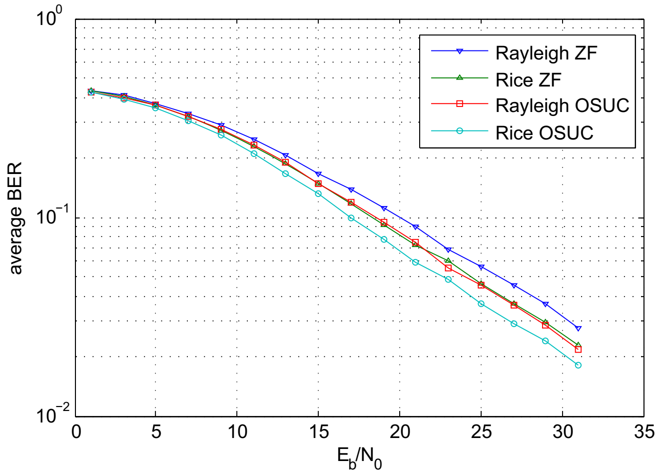

Fig. 8. Average bit error ratio of zero-forcing and cancellation receiver in Rayleigh and Rician fading channel in collision slots of two tags.

the measurements carried out by Kim et. al. [15]. The single Rayleigh channel coefficients are independent zero mean circularly symmetric complex Gaussian random variables with normalised energy $E\{|h_i|^2\} = 1$, meaning that the two tags participating in the collision, experience the same path loss. In the Rician channel the Rice factor is set to 2.8dB, according to the measurement results for Scenario 3 in [15]. In addition to disturbance by noise, each stream is interfered by the second tag response in the same slot, with the same average signal power.

VII. Discussion and Conclusion

This work proposes two receiver architectures for recovering from collisions of up to two tags at a physical layer. In contrast to conventional RFID readers, where collisions are resolved on a MAC layer, we explore the multiple access RFID uplink channel and the signal constellations at the reader receiver. The collision resolution receivers proposed, exploit the fact that the one-dimensional tag on-off keying modulation is embedded in the two dimensional I/Q baseband plane of the reader receiver. Applying geometric subspace considerations, the various signal constellation states are estimated, and the collided signal of two tags are recovered. The functionality of the proposed algorithms is shown on measurement data, and simulations show the performance of both receivers in different channels.

Combining the proposed receivers with framed slotted aloha, requires a different configuration of the protocol parameters compared state-of-the-art to readers. The expected theoretical throughput increase is shown to be approximately 1.6 times the throughput of a conventional reader.

While RFID system performance increase often is prevented by limited tag performance, the signal processing complexity increase of the proposed system is shifted to the RFID reader. Further, the proposed receivers operate with off-the-shelf RFID tags and are fully compliant to the EPCglobal standard for UHF RFID. Hence, the proposed receivers can directly be implemented on RFID readers to work with commercial tags.

Finally, we want to emphasise, that the proposed techniques are feasible as the various RFID tags participating in a collision backscatter the same carrier wave, which originates from the same source. Thus, all signals present in the system are modulated to the same carrier frequency, which is known to the reader receiver. This enables the joint downconversion process of all tag responses.

Equipping the reader receiver with multiple receive antennas, additionally enables the exploitation of different spatial signatures. Future research will focus on this topic, employing also multi-antenna spatial multiplexing with FSA in multiple tag RFID scenarios.

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