A Collision Recovery Receiver for RFID

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Outline

1. Introduction
2. Multi Antenna RFID Reader
3. Channel Estimation
4. Performance Analysis
5. Conclusion
Outline

1 Introduction

2 Multi Antenna RFID Reader

3 Channel Estimation

4 Performance Analysis

5 Conclusion
Introduction

- RFID - Radio Frequency Identification
- Wireless identification technology
- Allows non line of sight identification
- Multiple goods can be inventoried almost simultaneously
Challenges and Motivation

- Several RFID tags operate in reader range
- Multiple tags respond simultaneously
  - collision occurs
  - information is discarded
  - throughput decreases
- Motivation
  - use information from colliding tags
  - throughput increases
Multiple tags in RFID systems are scheduled by a medium access control layer using the FSA (EPCglobal)

- Query, Frame Size $F$
- Slot 0, Slot 1, Slot 2, Slot 3, Slot 4, Slot $F-1$
- RN $[0, F-1]$
- Tag 0, Tag 1, Tag 2, Tag 3, Tag N-1
- RN16

**Abbreviations:**
- $F$: selected frame size
- $N$: tag population size
- RN: random number
- Qr: Query repeat
- RN16: 16 bit Random number packet
Background and Previous Work

- Slots with single tag response can be decoded successfully

FSA: Framed Slotted Aloha

- $R$: number of tags transmitting in the same slot
- $N_{RA}$: number of receiving antennas on the reader
- $M$: collision recovery factor

Angerer, 2010
Background and Previous Work

- Slots with single tag response can be decoded successfully
- An antenna array + physical layer collision recovery receivers
Background and Previous Work

- Slots with single tag response can be decoded successfully
- An antenna array + physical layer collision recovery receivers
  - an increase of the theoretical throughput for the FSA RFID
  - recovering from collisions of two tags [Angerer, 2010]
    (single antenna receivers and channel estimation)
  - recover from a collision of a $R \leq N_{RA}$ [Angerer, 2010]
    (multiple antenna receivers and perfect channel knowledge)

**Abbreviations**
- FSA Framed Slotted Aloha
- $R$ number of tags transmitting in the same slot
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Collision Scenario

- Single transmit and $N_{RA}$ receive antennas
- The complex-valued baseband signal at the receive antenna $i$:

\[
s_{c,i}(t) = \sum_{j=1}^{R} h_{i,j}a_j(t) + l_i(t) + n_i(t), \quad i = 1, \ldots, N_{RA}
\]

- $h_{i,j}$: channel coefficient
- $a_j(t)$: modulation signal of tag $j$
- $l_i(t)$: carrier leakage at the $i^{th}$ antenna (assumed to be perfectly canceled)
- $n_i(t)$: noise at the $i^{th}$ antenna
Collision Scenario

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- The complex-valued baseband signal at the receive antenna $i$:

$$s_{c,i}(t) = \sum_{j=1}^{R} h_{i,j} a_j(t) + l_i(t) + n_i(t), \quad i = 1, \ldots, N_{RA}$$

- Vector form:

$$s_c(t) = H_c a(t) + l(t) + n(t)$$

- Considering that $a_j(t)$ is real-valued:

$$\begin{bmatrix} \Re\{s_c(t)\} \\ \Im\{s_c(t)\} \end{bmatrix} = \begin{bmatrix} \Re\{H_c\} \\ \Im\{H_c\} \end{bmatrix} a(t) + \begin{bmatrix} \Re\{l(t)\} \\ \Im\{l(t)\} \end{bmatrix} + \begin{bmatrix} \Re\{n(t)\} \\ \Im\{n(t)\} \end{bmatrix}$$

- $h_{i,j}$: channel coefficient
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Performance Increase in FSA

- Throughput increase by acknowledging more than one tag
- The throughput is:

\[ T = \sum_{R=1}^{J} \binom{N}{R} \left( \frac{1}{F} \right)^R \left( 1 - \frac{1}{F} \right)^{N-R} R + \sum_{R=J+1}^{M} \binom{N}{R} \left( \frac{1}{F} \right)^R \left( 1 - \frac{1}{F} \right)^{N-R} J \]
Performance Increase in FSA

- Throughput increase by acknowledging more than one tag
- The throughput is:

\[
T = \sum_{R=1}^{J} \binom{N}{R} \left( \frac{1}{F} \right)^R \left( 1 - \frac{1}{F} \right)^{N-R} R + \sum_{R=J+1}^{M} \binom{N}{R} \left( \frac{1}{F} \right)^R \left( 1 - \frac{1}{F} \right)^{N-R} J
\]

<table>
<thead>
<tr>
<th>System</th>
<th>$F_{opt}/N$</th>
<th>Exp. Thr.</th>
<th>Rel. Impr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M = 1 \ J = 1$</td>
<td>1</td>
<td>0.368</td>
<td>1.000</td>
</tr>
<tr>
<td>$M = 2 \ J = 2$</td>
<td>0.618</td>
<td>0.841</td>
<td>2.285</td>
</tr>
<tr>
<td>$M = 4 \ J = 2$</td>
<td>0.391</td>
<td>1.415</td>
<td>3.845</td>
</tr>
<tr>
<td>$M = 8 \ J = 1$</td>
<td>0.265</td>
<td>0.962</td>
<td>2.614</td>
</tr>
<tr>
<td>$M = 8 \ J = 2$</td>
<td>0.235</td>
<td>1.852</td>
<td>5.033</td>
</tr>
</tbody>
</table>

$N$ tag population (1 000)
$F$ frame size
$M$ collision recovery factor
$J$ number of acknowledged tags
MMSE receiver is used for collision recovery

The signal at the output of the MMSE receiver is:

$$r_{\text{MMSE}}(t) = \left( \hat{H}^H \hat{H} + \sigma^2 I_R \right)^{-1} \hat{H}^H \cdot \left( s(t) - \hat{H} \bar{a}(t) \right)$$

where:

- $H = \begin{bmatrix} \Re \{ H_c \} \\ \Im \{ H_c \} \end{bmatrix}$
- $s(t) = \begin{bmatrix} \Re \{ s_c(t) \} \\ \Im \{ s_c(t) \} \end{bmatrix}$
Channel Estimation

- Extension of the tag signal by including “postpreamble”

<table>
<thead>
<tr>
<th>preamble</th>
<th>RN16</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>preamble</th>
<th>postpreamble</th>
<th>RN16</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- In order to fulfill the channel estimation requirements, our “postpreamble” is designed to be:
  - different for each tag
  - and mutually orthogonal

RN16 16 bit Random number packet
Design of the “postpreamble”

- Length of the “postpreamble” is influenced by the number of the tags we want to separate

\[
T_k(p) = \begin{cases} 
1, & k = l \\
0, & \text{else} 
\end{cases}, \quad \forall p_k, p_l \in S_i
\]

Set of mutually orthogonal sequences
Design of the “postpreamble”

- Length of the “postpreamble” is influenced by the number of the tags we want to separate
- FM0 coding:
Design of the “postpreamble”

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  - doubles the amount of bits after the encoding process
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Design of the “postpreamble”

- Length of the “postpreamble” is influenced by the number of the tags we want to separate
- FM0 coding:
  - doubles the amount of bits after the encoding process
  - does not allow the use of well known orthogonal sequences (i.e., Hadamard)
- Search-algorithm:
The algorithm iterates over increasing set sizes and in each iteration it searches for all unique sets of mutually orthogonal sequences $p$ of the size of the particular iteration.

$$
p_k^T p_l = \begin{cases} 
1, & k = l \\
0, & \text{else,}
\end{cases}
$$

$\forall p_k, p_l \in S_i$

*$S_i*$ set of mutually orthogonal sequences
Least Squares estimator - LS

- LS estimator:
  \[
  \hat{H}_{\text{LS}} = \arg \min_{H} \| r - HS_{R_{\text{max}}} \|^2
  \]

- LS channel estimator for the “postpreamble”
  \[
  \hat{H}_{\text{LS}} = r \cdot S_{R_{\text{max}}}^H (S_{R_{\text{max}}} S_{R_{\text{max}}}^H)^{-1}
  \]

<table>
<thead>
<tr>
<th>Sequence</th>
<th>( p_1 )</th>
<th>1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_{18} )</td>
<td>1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1</td>
<td></td>
</tr>
<tr>
<td>( p_{69} )</td>
<td>1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1</td>
<td></td>
</tr>
<tr>
<td>( p_{86} )</td>
<td>1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1</td>
<td></td>
</tr>
<tr>
<td>( p_{171} )</td>
<td>1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1</td>
<td></td>
</tr>
<tr>
<td>( p_{188} )</td>
<td>1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1</td>
<td></td>
</tr>
<tr>
<td>( p_{239} )</td>
<td>1 1 -1 1 1 1 -1 1 -1 1 1 1 -1 1 -1 1 -1 1 -1</td>
<td></td>
</tr>
<tr>
<td>( p_{256} )</td>
<td>1 1 -1 1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1</td>
<td></td>
</tr>
</tbody>
</table>
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## Simulation Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of receiving antennas</td>
<td>$N_{RA} = 1, 2, 3, 4$</td>
</tr>
<tr>
<td>Number of responding tags</td>
<td>$R = 1, 2, 4, 8$</td>
</tr>
<tr>
<td>Channel</td>
<td>Double Rayleigh fading channel</td>
</tr>
<tr>
<td></td>
<td>Perf. knowledge of “postpreamble” set</td>
</tr>
</tbody>
</table>

### Diagram

```
Reader
  Tx
  Rx
```

---

A Collision Recovery Receiver for RFID

2012-05-22 12/17
BER for MMSE receiver and R=2

MMSE receiver with R=2 (perfect channel)

Average SNR [dB] | BER
---|---
-15 | 10^{-5}
-10 | 10^{-4}
-5  | 10^{-3}
0   | 10^{-2}
5   | 10^{-1}
10  | 10^0
15  | 10^1
20  | 10^2
25  | 10^3
30  | 10^4

MMSE receiver with R=2 (estimated channel)

A Collision Recovery Receiver for RFID

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BER for MMSE receiver and $R=2$

![Graph showing BER for MMSE receiver with perfect and estimated channels for different RA values.](image)

<table>
<thead>
<tr>
<th>BER at 30 dB</th>
<th>Perfect Channel</th>
<th>Estimated Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{RA} = 1$</td>
<td>$2.53 \times 10^{-2}$</td>
<td>$2.66 \times 10^{-2}$</td>
</tr>
<tr>
<td>$N_{RA} = 2$</td>
<td>$0.92 \times 10^{-3}$</td>
<td>$1.03 \times 10^{-3}$</td>
</tr>
<tr>
<td>$N_{RA} = 3$</td>
<td>$2.17 \times 10^{-4}$</td>
<td>$2.86 \times 10^{-4}$</td>
</tr>
<tr>
<td>$N_{RA} = 4$</td>
<td>$0.89 \times 10^{-4}$</td>
<td>$1.16 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

A Collision Recovery Receiver for RFID
BER for MMSE receiver and $R=4$

BER at 30 dB

<table>
<thead>
<tr>
<th>$N_{RA}$</th>
<th>Perfect Channel</th>
<th>Estimated Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.2049</td>
<td>0.2052</td>
</tr>
<tr>
<td>2</td>
<td>$1.21 \cdot 10^{-2}$</td>
<td>$1.36 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>3</td>
<td>$5.77 \cdot 10^{-4}$</td>
<td>$7.43 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>4</td>
<td>$1.61 \cdot 10^{-4}$</td>
<td>$2.15 \cdot 10^{-4}$</td>
</tr>
</tbody>
</table>
BER for MMSE receiver and R=8

<table>
<thead>
<tr>
<th>BER at 30 dB</th>
<th>Perfect Channel</th>
<th>Estimated Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{RA} = 1$</td>
<td>0.3170</td>
<td>0.3171</td>
</tr>
<tr>
<td>$N_{RA} = 2$</td>
<td>0.1842</td>
<td>0.1843</td>
</tr>
<tr>
<td>$N_{RA} = 3$</td>
<td>$7.53 \cdot 10^{-2}$</td>
<td>$7.56 \cdot 10^{-2}$</td>
</tr>
<tr>
<td>$N_{RA} = 4$</td>
<td>$5.66 \cdot 10^{-3}$</td>
<td>$7.17 \cdot 10^{-3}$</td>
</tr>
</tbody>
</table>
Throughput $J \leq 2$

The expected throughput of FSA ($J \leq 2$) for different configurations is shown in the graph. The throughput is calculated as the average number of successfully read tags per slot.

The throughput at $30 \text{ dB}$ is tabulated below for different configurations of $N_{RA}$, $R$, and $J$:

<table>
<thead>
<tr>
<th>$N_{RA}$</th>
<th>$R$</th>
<th>$J$</th>
<th>Throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.3533</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>2</td>
<td>0.7481</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>2</td>
<td>1.3830</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>2</td>
<td>1.8370</td>
</tr>
</tbody>
</table>

The throughput is compared between a perfect channel and an estimated channel. For a perfect channel, the throughput is as follows:

- $N_{RA} = 1, R = 1, J = 1$: 0.3533
- $N_{RA} = 1, R = 2, J = 2$: 0.7481
- $N_{RA} = 2, R = 4, J = 2$: 1.3830
- $N_{RA} = 4, R = 8, J = 2$: 1.8370

For an estimated channel, the throughput is:

- $N_{RA} = 1, R = 1, J = 1$: 0.3522
- $N_{RA} = 1, R = 2, J = 2$: 0.7445
- $N_{RA} = 2, R = 4, J = 2$: 1.3810
- $N_{RA} = 4, R = 8, J = 2$: 1.8370

The graph also shows the number of acknowledged tags for each configuration, with solid lines representing the perfect channel and dotted lines the estimated channel.
Conclusions

- Physical layer collision recovery:
  - 2.6 times throughput increase (J=1)
  - 5.0 times throughput increase (J=2)

- Proposed a method for channel estimation in collision scenarios

- Channel estimation method provides excellent results with perfect knowledge of the “postpreamble” set
Thank you for your attention!

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References


