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A Collision Recovery Receiver for RFID

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Outline

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Introduction

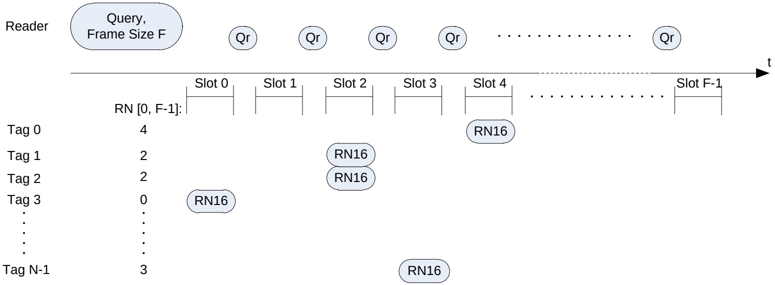
- RFID - Radio Frequency Identification
- Wireless identification technology
- Allows non line of sight identification
- Multiple goods can be inventoried almost simultaneously

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

Framed Slotted Aloha (FSA)

- Multiple tags in RFID systems are scheduled by a medium access control layer using the FSA (EPCglobal)



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

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- 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)

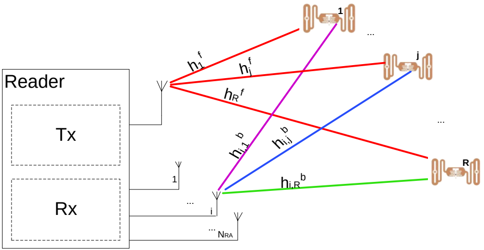
FSA	Framed Slotted Aloha
R	number of tags transmitting in the same slot
N_{RA}	number of receiving antennas on the reader
M	collision recovery factor

Outline

Collision Scenario

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

$$s_{\mathrm{c},i}(t) = \sum_{j=1}^{R} h_{i,j} a_j(t) + I_i(t) + n_i(t), \qquad i = 1, .., N_{\mathrm{RA}}$$



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

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- Vector form:

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

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

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

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Performance Increase in FSA

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

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

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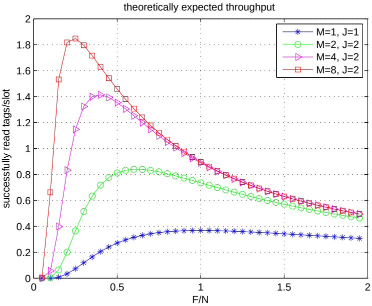


System	F_{opt}/N	Exp. Thr.	Rel. Impr.
$M=1$ $J=1$	1	0.368	1.000
$M=2$ $J=2$	0.618	0.841	2.285
$M=4$ $J=2$	0.391	1.415	3.845
$M=8$ $J=1$	0.265	0.962	2.614
$M=8$ $J=2$	0.235	1.852	5.033

N	tag population (1 000)
F	frame size
M	collision recovery factor
J	number of acknowledged tags

Receiver for Collision Recovery

- MMSE receiver is used for collision recovery
- The signal at the output of the MMSE receiver is:

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

  – where:

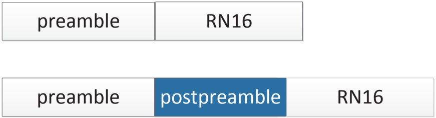
$$\mathbf{H} = \begin{bmatrix} \Re\{\mathbf{H_c}\} \\ \Im\{\mathbf{H_c}\} \end{bmatrix} \qquad \mathbf{s}(t) = \begin{bmatrix} \Re\{\mathbf{s_c}(t)\} \\ \Im\{\mathbf{s_c}(t)\} \end{bmatrix}$$

MMSE	Minimum Mean Square Error Receiver
$\hat{\mathbf{H}}$	matrix of the estimated channel
$\hat{\mathbf{H}}^H$	its Hermitian transpose
$\bar{\mathbf{a}}(t)$	$E\{\mathbf{a}(t)\}$
σ^2	the noise power
$\mathbf{I}_R$	$R \times R$ identity matrix

Outline

Channel Estimation

- Extension of the tag signal by including "postpreamble"



- 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”

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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.

$$\mathbf{p}_k^{\mathrm{T}}\mathbf{p}_l = \begin{cases} 1, & k = l \\ 0, & else, \end{cases}$$

$$\forall \mathbf{p}_k, \mathbf{p}_l \in \mathbf{S}_i$$

$\mathbf{S}_i$ set of mutually orthogonal sequences

Least Squares estimator - LS

- LS estimator:

$$\hat{\mathbf{H}}_{\mathrm{LS}} = \arg\min_{\mathbf{H}} \left\| \mathbf{r} - \mathbf{H}\mathbf{S}_{\mathrm{R_{max}}} \right\|^2$$

- LS channel estimator for the "postpreamble"

$$\hat{\mathbf{H}}_{\mathrm{LS}} = \mathbf{r} \cdot \mathbf{S}_{\mathrm{R_{max}}}^{H} (\mathbf{S}_{\mathrm{R_{max}}} \mathbf{S}_{\mathrm{R_{max}}}^{H})^{-1}$$

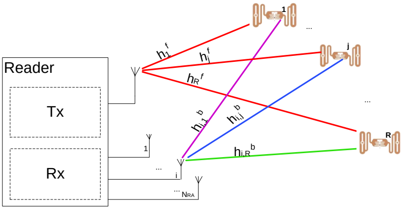
Sequence	
$\mathbf{p}_1$	1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1 1 -1
$\mathbf{p}_{18}$	1 -1 1 -1 1 -1 1 1 -1 1 -1 1 -1 1 -1 -1
$\mathbf{p}_{69}$	1 -1 1 1 -1 1 -1 1 -1 1 -1 -1 1 -1 1 -1
$\mathbf{p}_{86}$	1 -1 1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1
$\mathbf{p}_{171}$	1 1 -1 1 -1 -1 1 -1 1 1 -1 1 -1 -1 1 -1
$\mathbf{p}_{188}$	1 1 -1 1 -1 -1 1 1 -1 -1 1 -1 1 1 -1 -1
$\mathbf{p}_{239}$	1 1 -1 -1 1 1 -1 1 -1 -1 1 1 -1 -1 1 -1
$\mathbf{p}_{256}$	1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 1 1 -1 -1

$\mathbf{S}_{\mathrm{R_{max}}}$	set of the $\mathrm{R_{max}}$ "postpreambles"
$\mathbf{r}$	part of the received signal containing the "postpreamble"

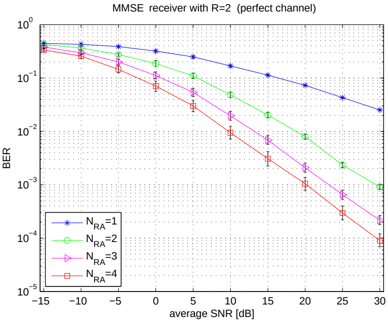
Outline

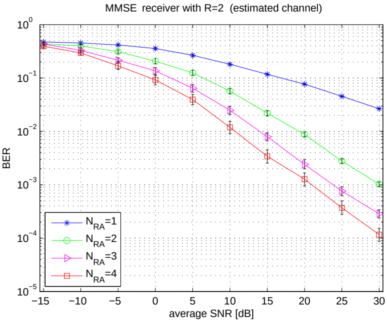
Simulation Setup

Simulation Parameters	Parameters Value
Number of receiving antennas	$N_{RA} = 1, 2, 3, 4$
Number of responding tags	$R = 1, 2, 4, 8$
Channel	Double Rayleigh fading channel
	Perf. knowledge of “postpreamble” set

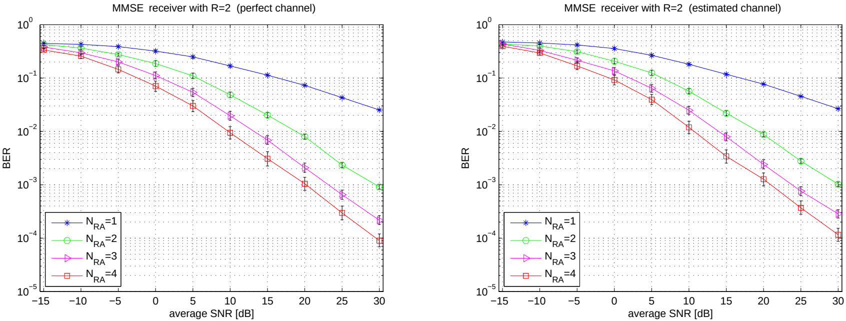


BER for MMSE receiver and R=2



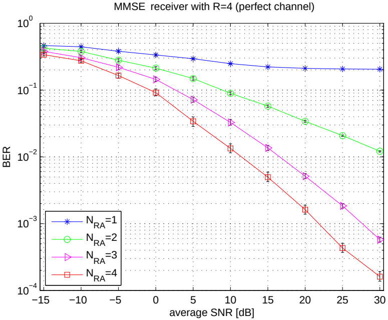


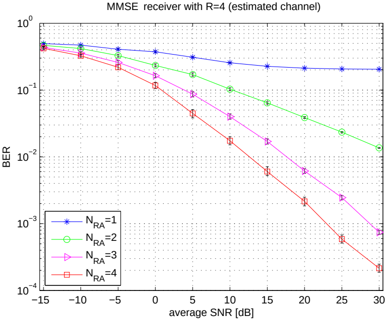
BER for MMSE receiver and R=2



BER at 30 dB	Perfect Channel	Estimated Channel
$N_{\mathrm{RA}} = 1$	$2.53 \cdot 10^{-2}$	$2.66 \cdot 10^{-2}$
$N_{\mathrm{RA}} = 2$	$0.92 \cdot 10^{-3}$	$1.03 \cdot 10^{-3}$
$N_{\mathrm{RA}} = 3$	$2.17 \cdot 10^{-4}$	$2.86 \cdot 10^{-4}$
$N_{\mathrm{RA}} = 4$	$0.89 \cdot 10^{-4}$	$1.16 \cdot 10^{-4}$

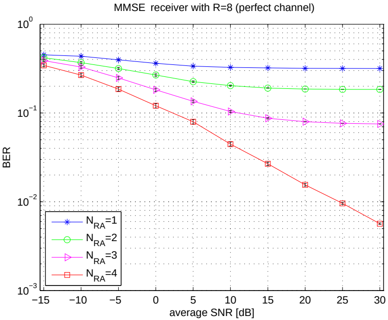
BER for MMSE receiver and R=4

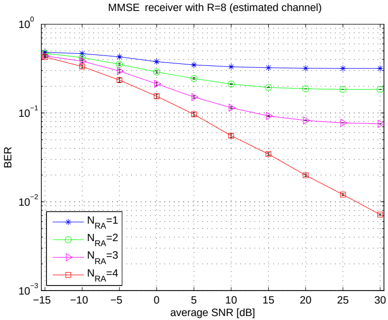




BER at 30 dB	Perfect Channel	Estimated Channel
$N_{\mathrm{RA}} = 1$	0.2049	0.2052
$N_{\mathrm{RA}} = 2$	$1.21 \cdot 10^{-2}$	$1.36 \cdot 10^{-2}$
$N_{\mathrm{RA}} = 3$	$5.77 \cdot 10^{-4}$	$7.43 \cdot 10^{-4}$
$N_{\mathrm{RA}} = 4$	$1.61 \cdot 10^{-4}$	$2.15 \cdot 10^{-4}$

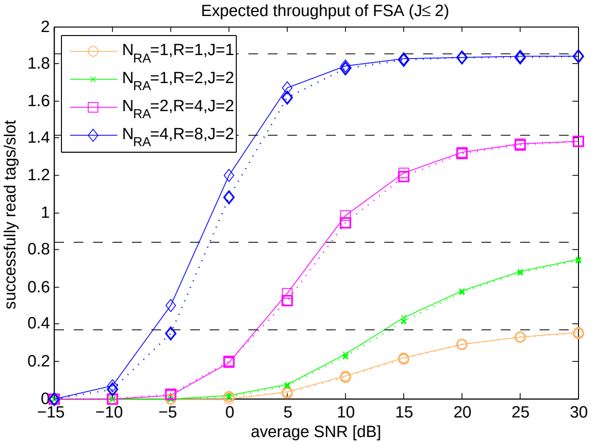
BER for MMSE receiver and R=8





BER at 30 dB	Perfect Channel	Estimated Channel
$N_{\mathrm{RA}} = 1$	0.3170	0.3171
$N_{\mathrm{RA}} = 2$	0.1842	0.1843
$N_{\mathrm{RA}} = 3$	$7.53 \cdot 10^{-2}$	$7.56 \cdot 10^{-2}$
$N_{\mathrm{RA}} = 4$	$5.66 \cdot 10^{-3}$	$7.17 \cdot 10^{-3}$

Throughput $J \leq 2$



Throughput at 30 dB			Perfect Channel	Estimated Channel
$N_{\mathrm{RA}} = 1$	$R = 1$	$J = 1$	0.3533	0.3522
$N_{\mathrm{RA}} = 1$	$R = 2$	$J = 2$	0.7481	0.7445
$N_{\mathrm{RA}} = 2$	$R = 4$	$J = 2$	1.3830	1.3810
$N_{\mathrm{RA}} = 4$	$R = 8$	$J = 2$	1.8370	1.8370

J	number of ack. tags
perf. channel	solid lines
est. channel	dotted lines

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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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