Maximal Ratio Combining Receivers for Dual Antenna RFID Readers

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***Abstract*— Radio frequency identification (RFID) systems at ultra high frequencies operate in an environment exposed to fading. While state-of-the-art RFID readers utilise multiple receive antennas with antenna multiplexing in order to deal with the multipath propagation environment, this contribution proposes maximal ratio combining at RFID reader receivers. A dual receive antenna RFID reader is presented in this paper. The composition of the receive signal and the constellation in the I/Q plane on each antenna is analysed and discussed thoroughly. With that knowledge, we design a receiver estimating the channel coefficients and realising maximal ratio combining of the received signals, thus achieving the optimum combination of receive signals in terms of SNR maximisation. Underlying assumptions on the receive signals at the RFID reader for the design of the receiver have been cross-verified with measurements. Furthermore, the receiver has been implemented on an FPGA and functionally verified.**

***Index Terms*— RFID, Reader Receiver, MIMO, Multiple Antenna, Receive Diversity, Maximal Ratio Combining**

I. Introduction

Radio Frequency Identification (RFID) is a wireless identification technology. In RFID systems, we distinguish between RFID readers and RFID tags. Furthermore, we classify tags into active and passive ones. While active tags carry their own power supply for processing and communicating, passive tags absorb energy from an electromagnetic field that is provided by the RFID reader and utilise a backscatter modulation for communication. Additionally, RFID systems are distinguished in their frequency bands. In this work we will only consider passive ultra high frequency (UHF) systems, operating in the frequency band from 865 - 950 MHz.

In passive UHF RFID, the propagation channel is strongly impaired by fading. Thorough theoretical analysis of the propagation channel from the reader transmitter to the tag backscatter and back to the reader receiver has been performed by Nikitin et al. for a single antenna reader receiver [1]. They also verified their models with measurements. A general model for both, a multiple antenna reader and a multiple antenna tag is proposed by Ingram et al. [2]. Griffin et al. [3] identify the theoretical performance increase using multiple antenna readers and multiple antenna tags by calculations and simulation, especially focusing on multiple antenna tags. Additionally, Nikitin et al. [4] present experimental results on read range increase and orientation insensitivity of RFID tags with multiple RF ports. Wang et al. [5] sketch a reader receiver performing maximal ratio combining, however do not present any realisation.

In order to combat multipath propagation, today's RFID readers utilise several receive antennas with antenna multiplexing, such as e.g. the RFID reader by Feig Electronics [6]. They simply multiplex the receive signals from the various receive antennas in a regular fashion.

With this work we designed the first digital RFID reader receiver performing maximal ratio combining (MRC). Thus, regarding the total signal to noise ratio (SNR) output, it combines the signals of two antennas in an optimal way. The advantage in contrast to antenna multiplexing is obvious: First, antenna multiplexing needs to multiplex all N_r receive antennas to identify the antenna with the highest SNR. Second, MRC always results in a stronger SNR than each of the single antenna receive paths. The trade-off is the duplication of the reader receive front-end and the increased signal processing complexity. The receiver has been implemented for a dual receive antenna reader, however it can be easily extended to multiple receive antennas.

II. Signals at the RFID Reader Receiver

Fig. 1 shows the basic communication between a tag and a multiple receive antenna 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. For transmitting information to the reader, tags use backscatter modulation. Thereby tags change from absorbing energy (tag absorb state, S_a) to reflecting energy (tag reflect state, S_r), by mismatching their antenna input impedance. At each antenna of the reader receiver, the tag modulation adds up with the carrier leakage. Fig. 2 shows this situation in the baseband I/Q plane of antenna i of the reader receiver: While the tag absorbs energy, the reader only discovers the carrier leakage (tag absorb state, $S_{a,i}$). If the tag backscatter-modulates information to the reader, this

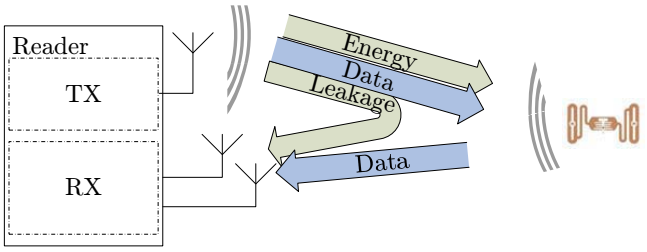


Fig. 1: RFID reader with two RX antennas.

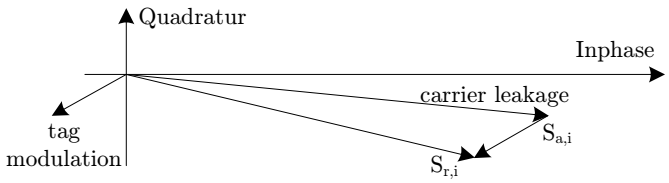


Fig. 2: Signals of antenna i at the reader receiver, IQ diagram.

modulation adds up with the carrier interference and gives a second state in the I/Q plane, the tag reflect state ($S_{r,i}$). At each single antenna, the reader can discriminate optimally between these two states as shown in [7]. The carrier interference is usually several magnitudes higher than the tag modulation signal (up to 80dB).

In general, the two tag states $S_{a,i}$ and $S_{r,i}$ can be located anywhere in the I/Q plane of the reader receiver: The location of the tag absorb state is determined by the phase and magnitude of the carrier leakage, which depends on the TX / RX decoupling concept and the spatial configuration (TX and RX antenna location). The location of the reflect state in the I/Q plane of the reader receiver is additionally determined by the signal received from the tag. Its phase and amplitude depend on the tag modulation behaviour (that is the two antenna input impedances the tag actually realises) and on the channel (attenuation and phase). It is important to notice, that in general first the $S_{a,i}$ and $S_{r,i}$ states originate form different sources, and hence are independent, and second, the received constellation points for $S_{a,i}$ and $S_{r,i}$ are independent on all receive antennas, due to different fading realisations and a different carrier leakage into the various receive paths.

III. Dual Antenna RFID Rapid Prototyping System

In order to verify the above considerations with measurements, the previously established RFID rapid prototyping platform [8] operating at 865-868 MHz was extended to a dual receive antenna prototyping system. The system consists of a digital baseband part, offering digital signal processing capabilities on a DSP and an FPGA, two digital-to-analogue converters (DAC) and two analogue-to-digital converters (ADC), and radio frequency (RF) frontends [9]. It constitutes a fully functional HF and UHF RFID reader, following amongst others the EPCglobal standard for UHF RFID [10]. The interface between analogue and digital domain

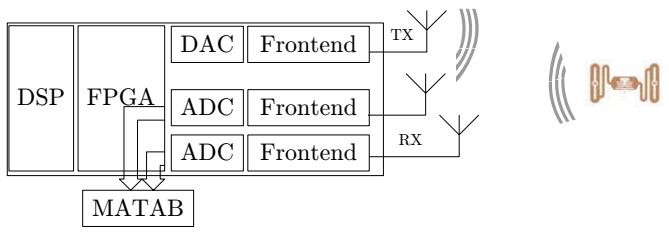
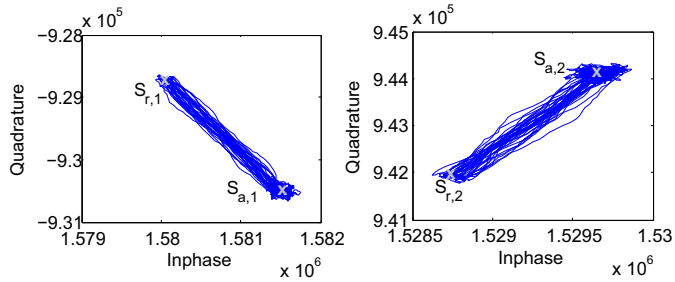


Fig. 3: Measurement setup: capture signals at two RX antennas.



(a) Antenna 1 (b) Antenna 2

Fig. 4: Tag response in baseband: inphase and quadrature constellations on both antennas.

is realised at an intermediate frequency of 13.33 MHz. In a first step, samples captured after the two independent ADCs on this rapid prototyping system during a measurement have been imported into Matlab (see Fig. 3).

Fig. 4 shows the receive sequences after I/Q demodulation and matched filtering, in the baseband of the reader receiver. If the tag modulation is assumed to have a rectangular shape, the matched filtering is realised by an integration, hence leading to a triangular output signal. One can clearly determine the two receive states $S_{a,i}$ and $S_{r,i}$ in both I/Q diagrams. Due to the matched filtering and the triangular shape of the signals, the receive samples move between the absorb and reflect state.

Comparing with the previous considerations of Fig. 2, we find that the location of the tag absorb states are defined by the carrier leakage, while the tag modulation adds up to realise the tag reflect state. The location in the I/Q plane is arbitrary, it depends on the phase and magnitude of the leaking carrier as well as on the channel and the tag modulation behaviour. Additionally, the situation on both antennas can be completely diverse, as shown in the example of Fig. 4 for phase and magnitude of both, the carrier leakage and the tag modulation.

IV. Maximal Ratio Combining at the RFID Reader Receiver

In terms of maximum SNR, the optimal combination method of multiple copies of the receive signal is maximal ratio combining:

$$s_c = \sum_{i=1}^{N_r} (s_{RX,i} - S_{a,i})\ h_i^* / \sigma_i^2. \tag{1}$$

The complex signal at antenna i and the combined signal are denoted as $s_{RX,i}$ and s_c respectively, while σ_i denotes the noise power at antenna i, and N_r is the total number of receive antennas. The channel coefficient h_i corresponds to the two-way reader-to-tag-to-reader channel, but not to the carrier interference. Its complex conjugate is denoted as h_i^*. As maximal ratio combining requires the knowledge of the channel coefficients and the noise power, channel estimation is required.

A. Channel Estimation

The channel coefficients are concluded from the tag states and are estimated separately for each antenna i [7]. The absorb state is estimated during ensured tag absorb times, i.e. between a reader command and the tag response (time interval T_1 in the EPCGlobal standard [10]). The temporal mean and the variance of the complex receive signal during that interval are used as an estimate for the absorb state S_a and the noise power respectively:

$$\hat{S}_{a,i} = E\{s_{RX,i}[k]\}_{T_1}, \tag{2}$$

$$\hat{\sigma}_i^2 = E\{|s_{RX,i}[k]|^2\}_{T_1} - |E\{s_{RX,i}[k]\}|^2_{T_1}. \tag{3}$$

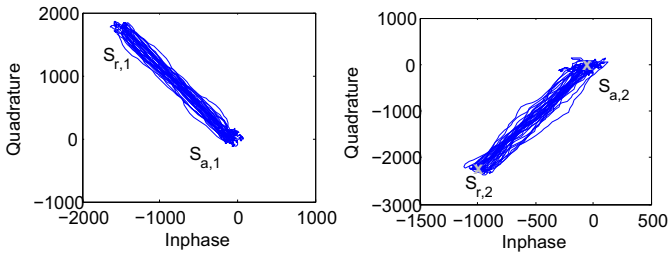
$E\{\cdot\}_{T_1}$ denotes the averaged value over time period T_1, and k is the sample index. With the tag starting to backscatter the carrier, the receive signal moves away from the absorb state in the reader receivers baseband I/Q plane. During the period of the first bit of the preamble of the tag response (t_{1bit}), the tag reflect state $S_{r,i}$ is estimated as the point at the largest distance from the tag absorb state in the I/Q plane:

$$\hat{S}_{r,i} = \max\{\left|s_{RX,i}[k] - \hat{S}_{a,i}\right|\}_{t_{1bit}}. \tag{4}$$

As soon as both states on all antennas are estimated, we first subtract the carrier interference, which does not carry any information (Fig. 5). This basically shifts the I/Q constellation of both antennas to the origin. The shifted tag reflect state now is comprised of the tag modulation behaviour and the channel coefficient (compare with Fig. 2). If the tag does not perfectly realise an on/off keying modulation, the attenuation and the phase shift due to the modulation affects all the estimates of the channel coefficients equally. As with such a scaling with a complex factor on all antennas MRC still guarantees the maximum possible SNR, we consider the modulation behaviour of the tag as part of the channel. Hence, each channel coefficient is reflected by the magnitude and phase of the shifted reflect state in the I/Q plane of each antenna:

$$\hat{h}_i = \hat{S}_{r,i} - \hat{S}_{a,i}. \tag{5}$$

It is important to note that the SNR on the various receive antennas may result from different receive signal powers or different noise levels in the individual receiver chains. A different receive signal strength is caused by different fading realisations on the various antennas. Distinct noise power levels can result from different transmitter / receiver decoupling schemes: If all receive branches are decoupled from the transmitter by separated antennas, equal noise power can be expected, and thus σ_i^2 can be omitted in Equation (1). If however the transmitter and one receive branch share one single antenna and the decoupling is achieved via a circulator or directional coupler, the noise power in this receive branch may be significantly higher, as noise generated by the transmit power amplifier leaks into the receiver via the circulator.



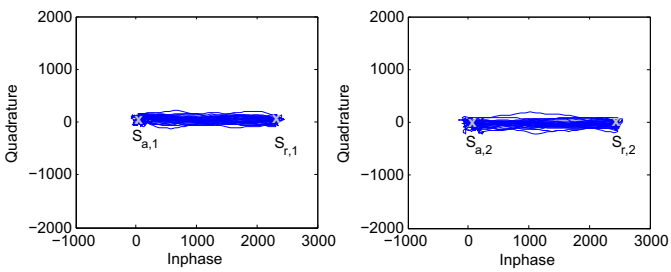
(a) Antenna 1 (b) Antenna 2

Fig. 5: Tag response in baseband with removed carrier leakage: inphase and quadrature constellations on both RX branches

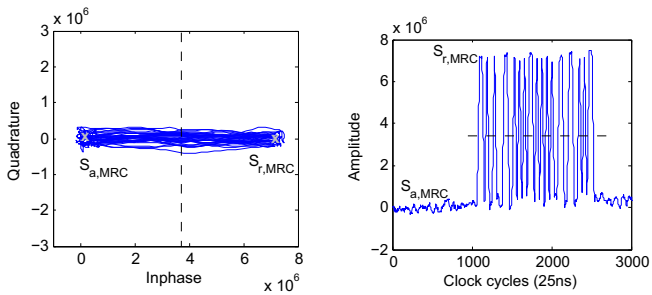
B. Realisation

After the estimation of the channel coefficients the various receive paths are combined according to Equation (1). The complex multiplications in Equation (1) are split into phase shifts and multiplications of magnitudes. The phase shift rotates the constellation at each antenna to 0 degrees. Fig. 6 shows the rotated constellations of the measured data for both antennas. Figures 6c shows the I/Q constellation diagram of the combined signal according to Equation (1). Finally, Fig. 6d shows the MRC combined signal in the time domain. After the maximal ratio combining, a threshold is set in the middle of the new, combined reflect and absorb states in order to discriminate optimally between them (according to a maximum likelihood detection). The estimated SNRs of the example data are 31.2dB and 32.4dB for antenna 1 and antenna 2 respectively, while the SNR for the combined signal is 33.8dB.

The presented algorithm achieves the following: It estimates the absorb and the reflect states on each antenna individually,



(a) Rotated constellation, Antenna 1 (b) Rotated constellation, Antenna 2



(c) Combined constellation, I/Q (d) Combined constellation, inphase component

Fig. 6: Tag response in baseband: maximal ratio combining.

and concludes the channel coefficient. The complex multiplication in maximal ratio combining is realised by a phase shift and a multiplication of magnitudes. As all the steps are processed sequentially (estimation of absorb state, estimation of reflect state, rotation to inphase component, multiplication of magnitudes and summation), the algorithm is suitable for real-time processing. It has been implemented on the FPGA of the established RFID prototyping system and functionally verified on hardware.

A block-diagram of the implemented receiver is shown in Fig. 7: The signals of both receive antennas are sampled at ADCs, I/Q downconverted and matched filtered. The channel estimation and maximal ratio combining are implemented as a finite state machine (FSM) in the subsequent slicer block. At the output of the slicer, the 0/1 encoded baseband signal is synchronised and decoded, before the receive bits are forwarded to the DSP for processing of the protocol. Registers and interrupts are utilised to exchange control information between DSP and FPGA. The rotation of the constellation on the hardware has been realised by a CORDIC algorithm.

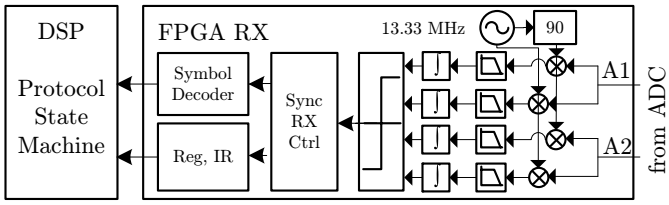


Fig. 7: Block-diagram of the receiver.

V. Conclusion and Discussion

In contrast to today's state of the art readers, where receive antennas are simply multiplexed and only one receive antenna at a time is considered, a realisation for maximal ratio combining of a dual antenna reader receiver has been shown. The realisation is not restricted to two receive antennas, and an extension to multiple antennas is straightforward. The combination is optimal in the sense of achieving maximum SNR at the reader receiver. The SNR gain comes with the trade-off of higher hardware and signal processing complexity.

An increase of the receive SNR compared to antenna multiplexing leads to an increase of the system reliability, especially in an environment with strong fading. However, this increase of SNR can also be traded into other performance goals, e.g. larger read-out distance or higher data throughput [11].

In fact, maximal ratio combining is a diversity combining technique. Hence, in a rich scattering environment with multipath propagation and fading this receiver exploits a diversity gain. However, if the receiver encounters equal fading realisations on both antennas or even AWGN (additive white gaussian noise) conditions, it can still exploit an array gain.

As the receiver estimates the channel coefficients on each antenna and combines the signals with the correct phase, no a-priori knowledge of the spatial installation is required. There are no pre-conditions on the antenna setup. Furthermore, it is worth noting, that the presented receiver does not require any specific standard changes, but can be applied to any UHF RFID system, and does not require any modification of RFID tags. The system performance increase comes with a modification at the reader receiver only.

This work shows a digital realisation of channel estimation and maximal ratio combining at an RFID reader receiver. The signal constellation at the single receive antennas in the baseband of the RFID reader receiver has been discussed in detail. Then, an estimation of the channel coefficients for the single antennas has been shown. In order to achieve maximal ratio combining, the complex multiplication has been split into a phase shift and a multiplication of magnitudes.

The underlying assumptions on the receive signal constellations at the reader for the development of the algorithm have been verified by measurement data. Further, the presented MRC processing is designed to suit for real-time processing. Finally, the algorithm has been implemented on an FPGA and functionally verified by measurements.

Future work will cover a performance comparison of the proposed receiver with different antenna selection schemes. Measurements in various environments are envisioned.

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