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The Application of Multiport Theory for MIMO RFID Backscatter Channel Measurements

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***Abstract*—This contribution deals with channel measurements in multiple-input multiple-output radio-frequency identification systems (MIMO RFID). Herein, multiple antennas are applied at the reader and at the RFID tag as well. A method for the determination of the channel coefficients between all antennas is presented. The channel information is needed to apply MIMO techniques to enhance the data rate or the reliability or range of the backscatter link. Since no measurement can be conducted at the tag antenna ports the method is based on the theory of determining the scattering parameters of a multiport (n-port) with a reduced number of measurement ports. Herein, the load impedances within the RFID tag being normally used to transmit information via backscatter modulation are used as known reflection standards. An internal thru standard between the tag antenna ports is introduced to reduce phase ambiguities. The method could be applied in future generations of multi-antenna RFID tags or could be used to characterize the channel for MIMO RFID prototype systems to evaluate their performance limits e.g. by calculating the MIMO capacity. Measurement results for the proposed method for a system with two reader transmit and receive and two tag antennas (2×2×2) are presented (5 to 6 GHz).**

***Index Terms*—RFID, MIMO, channel measurements, n-port, multiport, port reduction method**

I. Introduction

Within the last years the proliferation of RFID systems and technologies has increased enormously [1]. Besides the purpose of identifying goods, e.g. in supply chain management, RFID technologies become more and more important in other scenarios of data exchange, e.g. as an alternative to Bluetooth or ZigBee. For passive and semi-passive, i.e. battery-assisted RFID tags, the transmission of data between tag and reader relies on the principle of backscatter modulation by varying the mismatch between the tag antenna and its load. Thus, due to its dyadic channel structure, a backscatter system suffers from heavy path loss, which increases with the fourth power of the distance like in a radar system [2]. In multipath environments the system performance is additionally limited by fading effects, which are more severe than in classical "one way" communication systems [3].

Due to the demand for higher data rates or the extension of the achievable range or reliability, multi-antenna RFID systems with higher frequencies of operation have come into the focus of research, permitting the application of MIMO techniques. Within RFID systems multiple antennas can be used at the reader and at the tag as well. Fig. 1 depicts a scheme of a general $M \times L \times N$ MIMO RFID system, first introduced by [4]. The system can be characterized in the narrowband case with the complex baseband channel coefficients $h^f{}_{\mathrm{xy}}$ for the forward link and $h^b{}_{\mathrm{xy}}$ for the backscatter link.

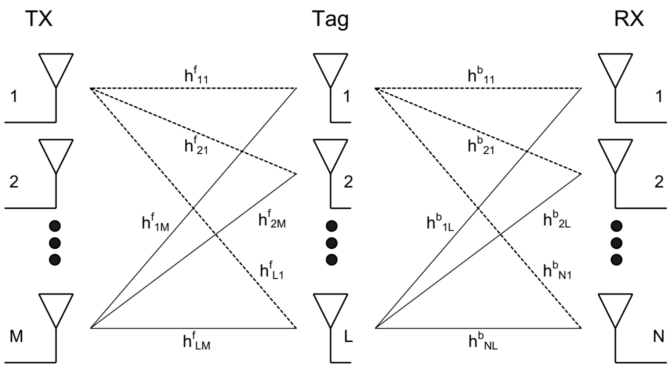

Figure 1. $M \times L \times N$ MIMO RFID system

The multiple antennas can be used for various purposes, e.g. at the receive (RX) array ($N > 1$) for enhancing the reliability or range via maximal ratio combing [5] or for collision recovery of multiple tags [6]. A transmit (TX) array ($M > 1$) can e.g. be used for enhancing the backscatter power of the tag via transmit diversity [7].

The multi-antenna RFID tag ($L > 1$) is characterized by the $L \times L$ signaling matrix consisting of the modulated reflection coefficients at each tag antenna and the internal transmission between the tag antennas [3]. When each antenna is modulated with the same signal and no internal transmission is present, the signaling matrix becomes a normalized identity matrix. When each antenna is modulated with an individual data stream (without transmission), the signaling matrix is a diagonal one. This type could be used for enhancing the data rate via spatial multiplexing [4] or the reliability via space time coding [8]. In case an additional transmission between the tag antennas is present the full signaling matrix exists. Until now only few applications for this type of signaling matrix have been revealed. One example is the application of the non-diagonal elements to realize retrodirective arrays [9].

To make MIMO techniques viable in RFID systems channel knowledge is usually necessary. Especially for the optimal exploitation of the available MIMO gains the channel state information (CSI) of the separated forward and backward link is essential. Regarding measurements of the complex channel

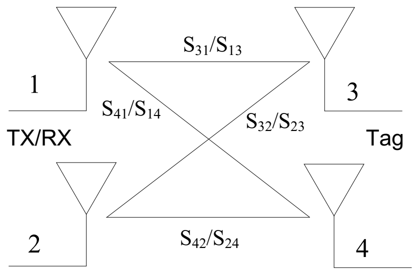

Figure 2. Scheme of the $2 \times 2 \times 2$ MIMO RFID system

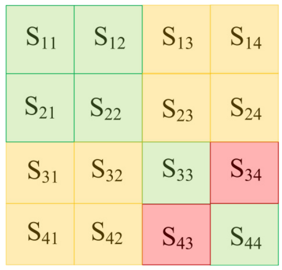

Figure 3. 4-port S-matrix of the $2 \times 2 \times 2$ MIMO RFID system

coefficients, in [10] fading measurements of the effective sum channel from TX to RX were conducted for a system with up to $1 \times 2 \times 2$ antennas by using a two antenna tag with identity signaling matrix. The individual channel coefficients between all antennas were not separated. In [6] a system with two RX and one TX antenna in conjuction with two individual tags at the same time was investigated. [7] conducts measurements for a reader configuration with four TX/RX-antennas and one tag antenna ($4 \times 1 \times 4$).

To the best knowledge of the authors, until now no method was published to determine all channel coefficients for a backscatter systems with multiple antennas at the reader (TX and RX) and at the tag. Therefore, this contribution deals with a measurement method to achieve knowledge of all complex channel coefficients. The method is based on the theory of measuring the scattering parameters of a multiport (n-port) with a reduced number of measurement ports and employs the full tag signaling matrix (Sec. II). Finally in Sec. III measurement results for the proposed method for a system with two reader (TX/RX) and two tag antennas ($2 \times 2 \times 2$) from 5 to 6 GHz are presented and compared to a reference measurement. A vector network analyzer (VNA) is used for the emulation of the multi-antenna RFID reader.

II. Proposed Measurement Method

In this section a method for determining the complex channel coefficients of MIMO RFID systems is presented. In contrast to other publications the scattering parameters between all antennas are taken into consideration, permitting e.g. to include the parasitic coupling between the reader antennas into investigations. Herein, the reader is able to transmit and receive with all antennas (TX/RX) and is capable to obtain the transmission between them. The method is exemplarily described for a $2 \times 2 \times 2$ system and should be adaptable to other configurations as long as at least one of the reader antennas is able to transmit and receive at the same time.

Since in this contribution the forward link is identical to the backward link, the general scheme of the MxLxN system (Fig. 1) is reduced to the scheme depicted in Fig. 2. The channel coefficients of interest (${h^f}_{\mathrm{xy}} = {h^b}_{\mathrm{xy}}$) are replaced by the corresponding scattering parameters ($S_{13} = S_{31}, S_{14} = S_{41}, S_{23} = S_{32}, S_{24} = S_{42}$), which are marked yellow in the resulting 4-port scattering matrix sketched in Fig. 3. In contrast to Fig. 1 here $S_{11}, S_{12} = S_{21}$ and S_{22} (green) are additionally taken into consideration, representing the reflection at reader antenna ports and the direct near field coupling as well as the transmission via scattering in the farfield (including the structural mode of the tag antennas but excluding the (modulated) scattering from the tag loads). In a time varying backscatter modulation these parameters are responsible for static signal portions which might limit the system's dynamic range and are thus worth being investigated.

Because passive or semi-passive RFID tags usually do not incorporate a full receiver hardware for coherent reception, the channel coefficients have to be obtained via measuring only at the reader ports. Thus, a method to determine the full scattering matrix without measuring at the tag antenna ports is necessary. A port reduction method (PRM) [11] is used and modified for this purpose, which is based on the theoretical fundament of the scattering matrix renormalization transform [12].

In general the used *Type-I PRM* renders possible the determination of the full scattering matrix of a n-port device by conducting three subset measurements with a VNA only at $(n-1)$ ports, when three different known terminations are connected to the n^{th} port. Here, the tag antenna ports are considered as ports for termination and the reader antenna ports are considered for measurement. When connecting a termination Γ_{n_x} to port n, the parameters $S_{ij}^{(n_\mathrm{x})}$ of the resulting $(n-1)$-port can be expressed in dependence of the parameters S_{ij} of the original n-port by the following equation, which are then measured and combined for all subsets to determine the parameters of the n-port:

$$S_{ij}^{(n_\mathrm{x})} = S_{ij} + \frac{S_{in} S_{nj} \Gamma_{n_\mathrm{x}}}{1 - S_{nn} \Gamma_{n_\mathrm{x}}} \ . \tag{1}$$

The *Type-I PRM* is conducted two times successively for two tag antennas, whereas the currently unused tag antenna has to be terminated with the reference impedance (Γ_0). For a practical RFID tag the scattering terminations could be realized e.g. by the scattering states of the signaling matrix, i.e. the constellation points of the modulation scheme, being normally used for scattering data. Backscatter modulators with more than two states are a topic of ongoing research at the moment (see e.g. [13] for 4-QAM).

A. Phase ambiguities

$S_{11}, S_{12} = S_{21}, S_{22}, S_{33}$ and S_{44} (green in Fig. 3) are determined unambiguously with the *Type-I PRM*. But since for reciprocal n-ports (as the MIMO RFID channel) the backscatter link parameters (yellow in Fig. 3) are determined by calculating the square root of the squared parameters, the

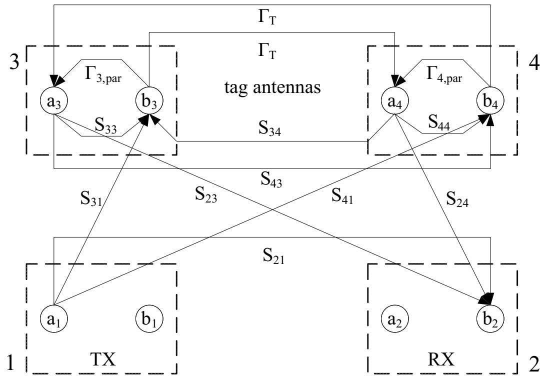

Figure 4. Signal-flow graph of the $2 \times 2 \times 2$ system for tag termination with Γ_T for one pair of TX/RX-antenna ports at $1, 2$

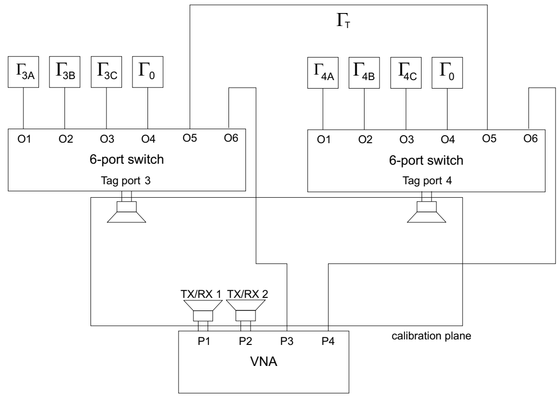

Figure 5. Measurement setup: 2x2x2 backscatter system

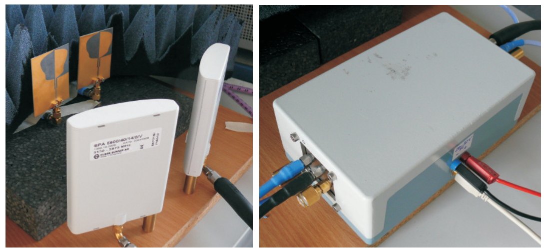

Figure 6. $2 \times 2 \times 2$ measurement setup; Agilent SP6T switches

method exhibits a sign (180° phase) ambiguity for each of those parameters *independently*. According to [11] this can be resolved with one additional measurement connecting the VNA to port n. Because this is impossible with real tags, another solution for removing the ambiguity has to be found.

For this purpose an additional subset measurement using an internal thru standard Γ_T between the tag antennas is proposed. The non-diagonal elements of the tag signaling matrix are thus being used to make a conjunction between different backscatter link scattering parameters. Fig. 4 depicts a signal-flow graph of the $2 \times 2 \times 2$ system for termination with Γ_T at the tag, exemplarily for one pair of transmitting and receiving reader ports $1, 2$. $\Gamma_{3/4,\mathrm{par}}$ denotes the parasitic reflections of the thru standard. In addition to the analytical terms from (1), signal-flow graph theory is applied to express the underlying analytical equation for the measurable scattering parameter $S^{\mathrm{T}}_{21,\mathrm{meas.}}$ in this case. $S^{\mathrm{T}}_{11,\mathrm{meas.}}$ and $S^{\mathrm{T}}_{22,\mathrm{meas.}}$ are expressed accordingly.

The equations are evaluated numerically for all possible solutions of the individual parameters with sign ambiguity (yellow in Fig. 3) by comparing them to the measured data. By this, it can be shown that with this additional measurement the remaining ambiguity can be reduced to two *common* solutions for all channel coefficients of the backscatter link (yellow in Fig. 3). A common constant factor (± 1) for all backscatter channel coefficients that are relevant for the data transmission can be accepted, since in the received signals at the reader each coefficient is taking part only multiplied by another one. Additionally, for investigations of information theoretical figures of merit, e.g. the capacity of the reverse link [4] does not change.

As indicated with red colour in Fig. 3, the scattering parameter $S_{34} = S_{43}$, representing the near field coupling and reflections from the far field between both tag antennas, is not determined with the proposed method, but has to be known due to its involvement in the reduction of phase ambiguities via evaluating the mentioned equations. Since the magnitude of far field reflections is usually low due to path loss, the near field coupling is assumed to dominate S_{34} and can either be neglected if sufficiently low or can be pre-characterized via simulation or measurement (assuming the near field is undisturbed in future measurements).

III. Measurement Results

To verify the capability of the proposed method, measurements were conducted with a $2 \times 2 \times 2$ setup containing two TX/RX reader antennas and two tag scattering antennas (i.e. a 4-port). A scheme and a photograph of the setup are shown in Fig. 5 and Fig. 6. The two-antenna semi-passive tag was emulated using two quasi-self-complementary UWB antennas connected to two Agilent SP6T switches (L7106B-T24) acting as switchable loads. Calibration standards from an Agilent calibration kit were used as scattering terminations. Each switch was equipped with "load" (Γ_0), "short" ($\Gamma_{3/4A}$), "open" ($\Gamma_{3/4B}$) and an open-ended 10 dB attenuator ($\Gamma_{3/4C}$). Since the input reflection coefficient of the switches is very low, the value of Γ_0 transformed to the antenna port can be assumed as a good match to the reference impedance ($|S_{11}| < -25$ dB). As the thru standard Γ_T a coaxial cable was used. Although not explicitly necessary, an additional measurement was conducted with both tag antennas scattering at once (Γ_{3A},Γ_{4B}) and the corresponding equation was additionally considered. The more measurements with different terminations are conducted, the more reliably the ambiguity can be reduced. Thus, over all 8 subsets of the effective 2-port were measured (Tab. I).

The terminations were characterized prior to the measurements (calibration plane at the switch input port). As indicated,

Tag port 3	Γ_{3A}	Γ_{3B}	Γ_{3C}	Γ_0	Γ_0	Γ_0	Γ_T	Γ_{3A}
Tag port 4	Γ_0	Γ_0	Γ_0	Γ_{4A}	Γ_{4B}	Γ_{4C}	Γ_T	Γ_{4B}

Table I
Subset measurements with the respective terminations

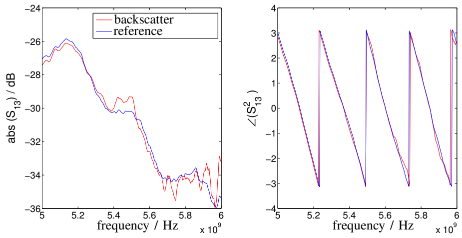

Figure 7. Backscatter and reference measurement results for S_{13}

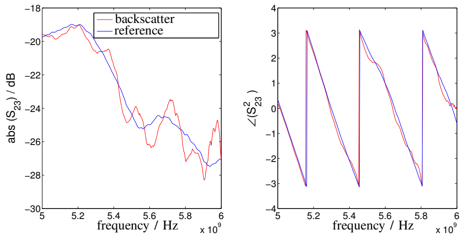

Figure 8. Backscatter and reference measurement results for S_{23}

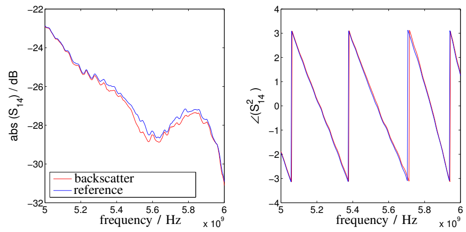

Figure 9. Backscatter and reference measurement results for S_{14}

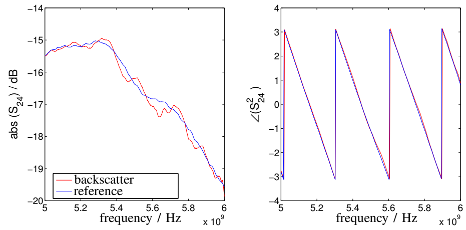

Figure 10. Backscatter and reference measurement results for S_{24}

a 4-port VNA (Rohde & Schwarz ZVA8) was used to emulate the RFID reader with two TX/RX patch antennas. The remaining two VNA-ports where used to measure the scattering matrix of the 4-port directly as a reference.

In Fig. 7 to 10 all backscatter link channel coefficients are depicted in magnitude and phase. For illustration purposes the phase is shown for the squared parameters due to the residual phase ambiguity of 180°. A good agreement both in magnitude and phase can be observed. The reduction of the sign ambiguities to two solutions in common for all channel coefficients as described in section II was successfully verified by comparison to the reference measurement.

IV. Conclusions

This contribution proposes a method for channel measurements in MIMO RFID systems with multiple antennas at the reader and at the tag. The method is based on the theory of measuring the scattering parameters of multiport devices with a reduced number of measurement ports. Herein, the load impedances within the tag and an additional thru standard are used as terminations, permitting the determination of all channel coefficients with a common sign ambiguity for all backscatter link parameters. The method could be applied in future generations of RFID readers in conjunction with multi-antenna tags or could be used to characterize the channel with MIMO RFID prototype systems to evaluate their performance limits e.g. by calculation the MIMO capacity. Measurement results for the proposed method for a system with two reader and two tag antennas have been presented. The method is validated by a good agreement of the results with a reference measurement.

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