On the Transmit Signal Design at the Reader for RFID MIMO Systems

Feng Zheng
Institute of Digital Signal Processing
University of Duisburg-Essen
47057 Duisburg, Germany
email: feng.zheng@uni-due.de

Thomas Kaiser
Institute of Digital Signal Processing
University of Duisburg-Essen
47057 Duisburg, Germany
email: thomas.kaiser@uni-due.de

***Abstract*—This paper discusses the reader's transmit signal design problem for RFID MIMO systems. First a mathematical model for this kind of system is developed from the viewpoint of signal processing. Then two spatial matching transmission schemes, namely matched to a fixed antenna at the tag or matched to a selected antenna at the tag, for the reader's signals are proposed. Simulation results illustrate that the proposed approaches can greatly improve the BER performance of RFID MIMO systems, compared to the uniform transmission policy.**

***Keywords*-RFID; MIMO; Transmit signal design; Reader.**

I. Introduction

Radio frequency identification (RFID) is a contactless, usually short distance, wireless data transmission and reception technique for identification of objects. It is believed that RFID can substitute, in the not-far future, the widely used optical barcode technology due to the limitations of the latter in i) the barcode cannot read non-line-of-sight (NLOS) tag; ii) each barcode needs personal care to be read; and iii) limited information-carrying ability of the barcode. Currently, a single antenna is usually used at the reader and tag of RFID in the market. However, RFID research community recently started to pay attention on using multiple antennas at either the reader side or the tag side [1], [2]. The reason is that using multiple antennas is an efficient approach for increasing the coverage of RFID, solving the NLOS problem, improving the reliability of data communications between the reader and tag, and thus further extending the information-carrying ability of RFID. Besides, some advanced technology in multiple transit and receive antennas (MIMO) can be used to solve the problem of detecting multiple objects simultaneously, see e.g., [3].

There have been several studies about RFID-MIMO. [4] first showed the idea of using multiple antennas at the reader for both transmission and reception. In [1], the authors first proposed to use multiple antennas at the tag and showed the performance gain by equipping multiple antennas at the reader (for both transmitting and receiving) and the tag. In [5], the multipath fading for both single-antenna based RFID channel and RFID-MIMO channel was measured and compared. The improvement on the fading depth by using MIMO can be clearly seen from the measured power distribution (see, e.g., Fig. 10 therein). In [6], the authors first proposed to apply the Alamouti space-time coding technique, which is now popularly used in wireless communication systems, to the RFID systems. [6] gave a closed-form expression for the bit-error rate (BER) of the RFID system with the none-coherent frequency shift keying modulation and multiple transmitter antennas at the tag and single transmit/receive antenna at the reader, where the double Rayleigh fading is assumed at the forward and backward links. In [7], the interrogation range of ultrahigh-frequency-band (UHF-band) RFID with multiple transmit/receive antennas at the reader and single antenna at the tag was analyzed, where the forward and backward channels are assumed to take the Nakagami-m distribution. In [3], the blind source separation technique in antenna array was used to solve the multiple tag identification problem, where the reader is equipped with multiple antenna. [8] applied the maximal ratio combining technique to the RFID receiver, where the channel of the whole chain, including forward link, backscattering coefficient, and backward link, was estimated and used as the weighting coefficient for the combining branches. [9] reported a prototype for the RFID-MIMO in the UHF-band. In [10], both MIMO-based zero-forcing and minimum-mean-square-error receivers were used to deal with the multiple-tag identification problem, where the channel of the whole chain was estimated, similar to the approach in [8]. It is reported in [11] that four antennas are fabricated in a given fixed surface at the reader. The measurement results showed that an increase of 83% in area gave a 300% increase in available power to turn on a given tag load and the operational distance of the powered device is increased to 100 cm by the four antenna setup from roughly 40 cm for the single antenna setup. The result in [11] suggests that the MIMO technique can be very promising to the RFID technology.

In the aforementioned reports, only MIMO-based receivers at the reader and the RF tag design are discussed. In this paper, we propose an approach to designing the transmit signals for the MIMO reader. The basic idea is to apply spatial matching principle to the multiple transmit antennas at the reader, so that the received signal at the tag is automatically strengthened. This strengthened power at

978-0-7695-4813-5/12 $26.00 © 2012 IEEE
DOI 10.1109/RFID.2012.11

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the tag plays two-fold role. First, the reflected power by the backscattering modulator at the tag is proportionally increased, and hence the received power at the reader is increased. Second, the incident power to the backscattering modulator is more stable due to the inherent high diversity of the MIMO forward channel. This byproduct is beneficial for keeping the tag in the power-on status while being illuminated.

The paper is organized as follows. A modified MIMO-RFID channel model will be developed in Section 2. It is this model that enables our spatial matching design, which will be discussed in Section 3. Section 4 presents the simulation results and Section 5 concludes the paper.

II. Channel Modeling of RFID MIMO Wireless Systems

The block diagram of the RFID MIMO system is illustrated in Fig. 1, where both the reader and tag are equipped with multiple antennas.

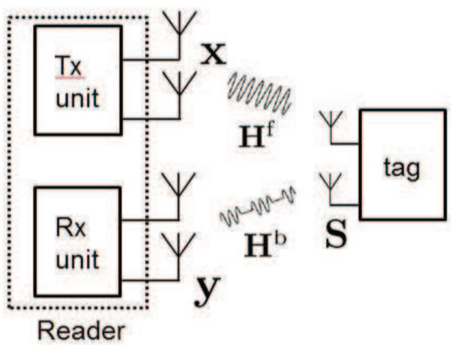


Figure 1. A block diagram of the RFID MIMO system.

In this paper our discussion is confined only on narrowband RFID systems. In terms of equation (1) of [1], the narrowband RFID MIMO wireless channel can be expressed as

$$\mathbf{y}(t) = \mathbf{H}^{\mathrm{b}}\mathbf{S}(t)\mathbf{H}^{\mathrm{f}}\mathbf{x}(t) + \mathbf{n}(t) \tag{1}$$

where the reader and tag are equipped with N_{rd} and N_{tag} antennas, respectively, $\mathbf{x}$ (an $N_{\mathrm{rd}} \times 1$ vector) is the transmitted signal at the reader, $\mathbf{y}$ (an $N_{\mathrm{rd}} \times 1$ vector) is the received signal at the reader, $\mathbf{n}$ is the receiver noise, $\mathbf{H}^{\mathrm{f}}$ is the channel matrix from the reader to the tag, $\mathbf{H}^{\mathrm{b}}$ is the channel matrix from the tag to the reader, and $\mathbf{S}$ is the backscattering matrix, which is also called signaling matrix. It is assumed that the N_{rd} antennas at the reader are used for both reception and transmission. This assumption is just for the brevity of the notation. It is straightforward to extend the approach presented in this paper to the case where the reader has different number of antennas for reception and transmission.

In most general case where the modulated backscatter signals at the tag are transferred between the antennas, the signaling matrix $\mathbf{S}$ is a full matrix [1]. However, no application of the full signalling matrix has been identified up to now [1]. Therefore, we will consider the situation where the RF tag antennas modulate backscatter with different signals and no signals are transferred between the antennas. In this case, the signaling matrix is a diagonal matrix [1]

$$\mathbf{S}(t) = \mathtt{diag}\left\{\Gamma_1(t),\ \Gamma_2(t)\ \ldots,\ \Gamma_{N_{\mathrm{tag}}}(t)\right\},\quad |\Gamma_i(t)| \le 1$$

where $\Gamma_i(t)$ the backscattering coefficient of ith antenna at the tag. The ith tag identification is contained in the coefficient $\Gamma_i(t)$.

Note that in the RFID system, the transmitted signal $\mathbf{x}$ is mainly used to adjust the transmit power, while the information data (i.e., tag ID) is carried out by $\mathbf{S}$. Therefore, the central issue for the RFID is to decode $\Gamma_1, \ldots, \Gamma_{N_{\mathrm{tag}}}$ from the received signal. Next we transform equation (1) to the conventional form in signal processing. Let us define

$$\boldsymbol{\gamma}(t) = \begin{bmatrix} \Gamma_1(t) \\ \Gamma_2(t) \\ \vdots \\ \Gamma_{N_{\mathrm{tag}}}(t) \end{bmatrix},\quad \mathbf{H}^{\mathrm{f}} = \begin{bmatrix} \mathbf{H}^{\mathrm{f}}_1 \\ \mathbf{H}^{\mathrm{f}}_2 \\ \vdots \\ \mathbf{H}^{\mathrm{f}}_{N_{\mathrm{tag}}}(t) \end{bmatrix} \tag{2}$$

Then equation (1) can be rewritten as

$$\begin{aligned}
\mathbf{y}(t) &= \mathbf{H}^{\mathrm{b}}\mathtt{diag}\left\{\Gamma_1(t),\ \Gamma_2(t)\ \ldots,\ \Gamma_{N_{\mathrm{tag}}}(t)\right\}\mathbf{H}^{\mathrm{f}}\mathbf{x}(t) + \mathbf{n}(t) \\
&= \mathbf{H}^{\mathrm{b}}\mathtt{diag}\left\{1,\ 0,\ \ldots,\ 0\right\}\mathbf{H}^{\mathrm{f}}\mathbf{x}(t)\Gamma_1(t) \\
&\quad + \mathbf{H}^{\mathrm{b}}\mathtt{diag}\left\{0,\ 1,\ \ldots,\ 0\right\}\mathbf{H}^{\mathrm{f}}\mathbf{x}(t)\Gamma_2(t) + \cdots \\
&\quad + \mathbf{H}^{\mathrm{b}}\mathtt{diag}\left\{0,\ 0,\ \ldots,\ 1\right\}\mathbf{H}^{\mathrm{f}}\mathbf{x}(t)\Gamma_{N_{\mathrm{tag}}}(t) + \mathbf{n}(t) \\
&= \mathbf{H}^{\mathrm{b}}\begin{bmatrix} \mathbf{H}^{\mathrm{f}}_1 \\ \mathbf{0} \\ \vdots \\ \mathbf{0} \end{bmatrix}\mathbf{x}(t)\Gamma_1(t) + \mathbf{H}^{\mathrm{b}}\begin{bmatrix} \mathbf{0} \\ \mathbf{H}^{\mathrm{f}}_2 \\ \vdots \\ \mathbf{0} \end{bmatrix}\mathbf{x}(t)\Gamma_2(t) \\
&\quad + \cdots + \mathbf{H}^{\mathrm{b}}\begin{bmatrix} \mathbf{0} \\ \mathbf{0} \\ \vdots \\ \mathbf{H}^{\mathrm{f}}_{N_{\mathrm{tag}}} \end{bmatrix}\mathbf{x}(t)\Gamma_{N_{\mathrm{tag}}}(t) + \mathbf{n}(t) \\
&= \mathbf{H}^{\mathrm{b}}\begin{bmatrix} \mathbf{H}^{\mathrm{f}}_1\mathbf{x}(t) & 0 & \cdots & 0 \\ 0 & \mathbf{H}^{\mathrm{f}}_2\mathbf{x}(t) & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \mathbf{H}^{\mathrm{f}}_{N_{\mathrm{tag}}}\mathbf{x}(t) \end{bmatrix} \\
&\quad \times \begin{bmatrix} \Gamma_1(t) \\ \Gamma_2(t) \\ \vdots \\ \Gamma_{N_{\mathrm{tag}}}(t) \end{bmatrix} + \mathbf{n}(t) \\
&= \mathbf{H}^{\mathrm{b}}\breve{\mathbf{H}}(t)\boldsymbol{\gamma}(t) + \mathbf{n}(t)
\end{aligned} \tag{3}$$

where

$$\breve{\mathbf{H}}(t) := \begin{bmatrix} \mathbf{H}_1^{\rm f}\mathbf{x}(t) & 0 & \cdots & 0 \\ 0 & \mathbf{H}_2^{\rm f}\mathbf{x}(t) & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \mathbf{H}_{N_{\rm tag}}^{\rm f}\mathbf{x}(t) \end{bmatrix}$$

Equation (3) transforms the original system model (1) into the conventional form in signal processing: the signal to be estimated or decoded is packed in a vector, whose entries are independent of each other.

III. Design of Reader Transmit Signals

It is generally required that the transmit power at the reader is as small as possible to minimize the interference to other radio systems. In this paper, it is assumed that the total transmit power at the reader across all the antennas is normalized to the unit, i.e., $\|\mathbf{x}\| = 1$. We will investigate how to distribute the transmit power at the reader to achieve good performance. According to the matching filter principle and from equation (3) it can be seen that one way to maximize the received power for some tag is to let $\mathbf{x}$ match to some spatial channels, say $\mathbf{H}_i^{\rm f}$. This leads to

$$\mathbf{x} = \frac{\mathbf{H}_{i_0}^{\rm f}}{\|\mathbf{H}_{i_0}^{\rm f}\|} \quad i_0 \in \{1, \ldots, N_{\rm tag}\} \tag{4}$$

where $\|\cdot\|$ denotes the 2-norm in the corresponding vector-space. Equation (4) says that we can only match the transmit signal to some specific branch of the multiple channels. One can further choose i_0 such that $\mathbf{H}_{i_0}^{\rm f}$ is of maximal power among all $\mathbf{H}_i^{\rm f}$'s, i.e.,

$$i_0 = \arg\max_i \|\mathbf{H}_i^{\rm f}\| \tag{5}$$

The combination of (4) and (5) maximally exploits the allowed transmit power of the reader.

At the reader receiver, the minimum-mean-square-error (MMSE) receiver is used to decode the information data $\boldsymbol{\gamma}$. Its estimate can be written as[1]

$$\hat{\boldsymbol{\gamma}} = \big(\mathbf{H}^{\rm b}\breve{\mathbf{H}}\big)^{\rm H}\boldsymbol{\Phi}\mathbf{y} = \big(\mathbf{H}^{\rm b}\breve{\mathbf{H}}\big)^{\rm H}\boldsymbol{\Phi}(\mathbf{H}^{\rm b}\breve{\mathbf{H}}\boldsymbol{\gamma} + \mathbf{n}) \tag{6}$$

where the superscript $^{\rm H}$ denotes the conjugate transpose of a matrix or vector,

$$\begin{aligned} \boldsymbol{\Phi} &= \Big[\mathbf{H}^{\rm b}\breve{\mathbf{H}}\big(\mathbf{H}^{\rm b}\breve{\mathbf{H}}\big)^{\rm H} + \rho\mathbf{I}\Big]^{-1} \\ &= \Big\{\mathbf{H}^{\rm b}D(\mathbf{H}^{\rm f})\|\mathbf{x}\|^2\big(\mathbf{H}^{\rm b}\big)^{\rm H} + \rho\mathbf{I}\Big\}^{-1} \end{aligned}$$

where

$$D(\mathbf{H}^{\rm f}) := \begin{bmatrix} \|\mathbf{H}_1^{\rm f}\|^2 & 0 & \cdots & 0 \\ 0 & \|\mathbf{H}_2^{\rm f}\|^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \|\mathbf{H}_{N_{\rm tag}}^{\rm f}\|^2 \end{bmatrix}$$

and ρ is a real positive parameter related with the power ratio between the signal $\boldsymbol{\gamma}$ and noise $\mathbf{n}$.

It can be seen that how to allocate the power of $\mathbf{x}$ does not affect the value of matrix $\boldsymbol{\Phi}$. It only affects the value of matrix $\breve{\mathbf{H}}$. From equation (6) we can see that the policy (4)-(5) maximizes the power ratio between the desired signal $\mathbf{H}^{\rm b}\breve{\mathbf{H}}\boldsymbol{\gamma}$ (or $\hat{\boldsymbol{\gamma}}$) and the noise $\mathbf{n}$. Because of the diagonal structure of matrix $\breve{\mathbf{H}}$, the power ratio maximization is applied to the selected i_0th tag, i.e., the signal branch for the i_0th tag identity (ID) will receive a maximal signal-to-noise power ratio (SNR), and hence will have best bit-error-rate (BER) performance.

IV. Simulation Results

When multiple antennas are equipped at the tag, there are two basic ways to modulate the backscattering coefficients $\boldsymbol{\gamma}$ among different antennas. The first way is that the backscatter circuits at different antennas use different data symbols (i.e., tag IDs) to modulate the backscattering coefficients, i.e., each tag antenna sends its own data symbol. In this case, the signal vector $\boldsymbol{\gamma}$ is of the general form as shown in equation (2). The second way is that all the backscatter circuits at different antennas use the same data symbol (i.e., tag ID) to modulate the backscattering coefficients and then transmit the reflected signal among different antennas. In this case, the signal vector $\boldsymbol{\gamma}$ is of the following form

$$\boldsymbol{\gamma}(t) = \Gamma_0(t)\begin{bmatrix} c_1 \\ c_2 \\ \vdots \\ c_{N_{\rm tag}} \end{bmatrix} \tag{7}$$

where $\Gamma_0(t)$ corresponds to the tag ID information, which is to be estimated, and $c_1, c_2, \ldots, c_{N_{\rm tag}}$ are constants, which is determined by the backscatter modulation circuits. For simpleness, we assume that $c_1 = \cdots = c_{N_{\rm tag}} = 1$

In the first case, the multiple antennas at the tag are mainly used to increase the data rate of RFID. In the second case, the multiple antennas at the tag are mainly used to increase the diversity of the wireless channel and hence to improve the BER performance of RFID.

First we investigate the system performance of MIMO RFID for the first case. In the simulations, both forward channel $\mathbf{H}^{\rm f}$ and backward channel $\mathbf{H}^{\rm b}$ take the Gaussian distribution, each entry of which is of zero mean and unity variance. Both $\mathbf{H}^{\rm f}$ and $\mathbf{H}^{\rm b}$ are independent of each other, and all the entries of $\mathbf{H}^{\rm f}$ and $\mathbf{H}^{\rm b}$ are mutually independent.

To compare, we also plotted the case where $\mathbf{x}$ is a random vector whose entry is uniformly distributed among $\pm\frac{1}{\sqrt{N_{\rm rd}}}$. It is seen that $\mathbf{x}$ is also of unity power.

In the figure to be shown, the SNR is defined as the ratio between the total power carried by signal vector $\boldsymbol{\gamma}$ and noise power at each receive antenna. The parameter ρ is chosen to be 1/SNR.

[1] Here we have used the fact that $\mathbf{A}^{\rm H}(\mathbf{A}\mathbf{A}^{\rm H} + \rho\mathbf{I})^{-1} = (\mathbf{A}^{\rm H}\mathbf{A} + \rho\mathbf{I})^{-1}\mathbf{A}^{\rm H}$, which holds true when ρ is sufficiently large so that both $\mathbf{A}\mathbf{A}^{\rm H} + \rho\mathbf{I}$ and $\mathbf{A}^{\rm H}\mathbf{A} + \rho\mathbf{I}$ are invertible for any matrix $\mathbf{A}$.

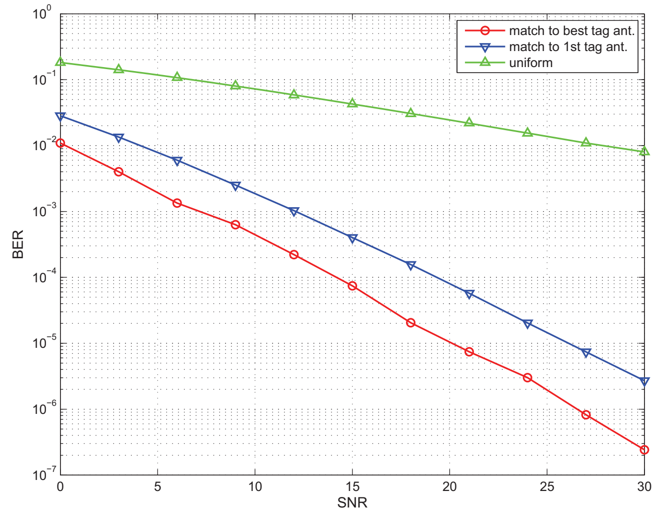
In the following figures, the curve marked with "match to best tag ant." means the BER for the data symbol transmitted at i_0th antenna at the tag, where the spatial matching policy (4)-(5) is applied; while the curve marked with "match to 1st tag ant." means the BER for the data symbol transmitted at the first antenna at the tag (i.e., the tag antenna with subscript 1), where the spatial matching policy (4) is applied to a fixed antenna (here means the first antenna) at the tag. The curve marked with "uniform" means the BER for the data symbols transmitted through all the tag antennas where the aforementioned uniformly-distributed random vector (thereafter denoted as uniform policy) is transmitted at the reader, i.e., no spatial matching policy is applied at the reader.

Fig. 2 shows the BERs for the case of $N_{\rm rd} = 4$ and $N_{\rm tag} = 2$. The BERs for three different symbols are plotted here. Fig. 2 (a) illustrates the BER for the optimally matched tag ID (i.e., the BER for the data symbol transmitted through the i_0th antenna at the tag), Fig. 2 (b) illustrates the BER for all the tag IDs (i.e., the BER for all the data symbols transmitted through the multiple antennas at the tag), and Fig. 2 (c) illustrates the BER for all other unmatched tag IDs (i.e., the BER for all other data symbols except the one transmitted through the i_0th antenna at the tag). It can be seen from Fig. 2 (a) that the spatial matching policy at the reader yields a great SNR gain for the optimally-matched tag ID compared to the uniform policy. Comparing the two curves marked with "match to best tag ant." and "match to 1st tag ant.", we can find that a further diversity gain is obtained by selecting the best channel among the two available spatial channels (two 4×1 channels). From Fig. 2 (b) and (c) we can see that the BERs for other data symbols or for all data symbols are roughly in the same order, even though the "uniform" policy yields a little better BER than the other two policies for the unmatched tag ID symbols. The reason for this phenomenon is that the good channel is used to transmit the selected tag ID, while other unfavored channels are used to transmit other tags' IDs. This is a sacrifice to the identification of other unfavored tags' IDs. However, it is seen from Fig. 2 (c) and Fig. 3 (c) that the BER performance sacrifice caused by the channel selection for the unfavored tags is quite limited.

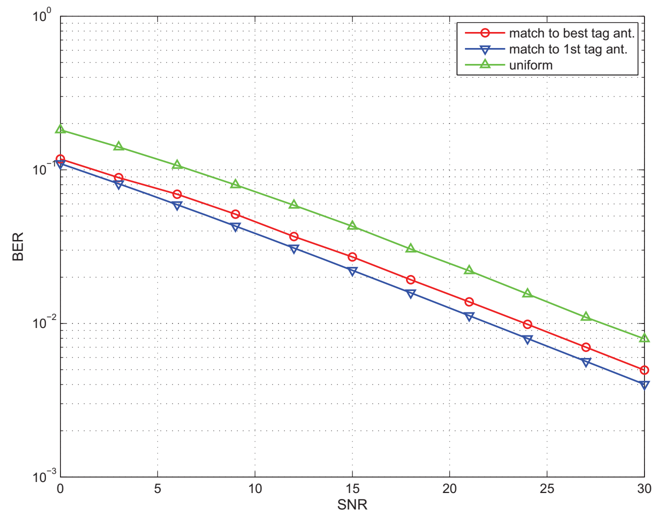
Fig. 3 shows the BERs for the case of $N_{\rm rd} = 4$ and $N_{\rm tag} = 4$. It shed the similar light on the usage of the spatial matching policy versus the uniform policy as Fig. 2 does. The major difference that worths to mention is that the SNR gain obtained by the spatial matching policy for the case of $N_{\rm tag} = 4$ is much greater than the case of $N_{\rm tag} = 2$.

Fig. 4 shows the BERs for the case of $N_{\rm rd} = 4$ and $N_{\rm tag} = 1$. As it can imagined, the case of "match to best tag ant." collapses to the case of "match to 1st tag ant.". This is indeed the case. We also see that both cases yields a great SNR gain than the uniform policy.

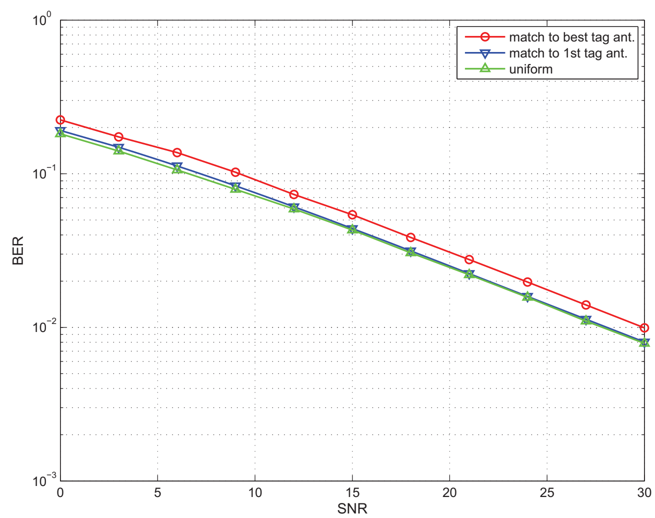
Fig. 5 shows the BER performance of the MIMO RFID



(a) for the optimally matched tag ID

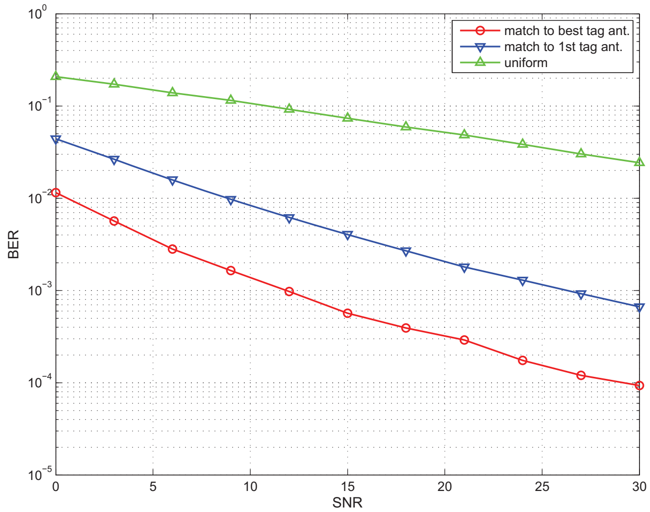


(b) for all the tag IDs

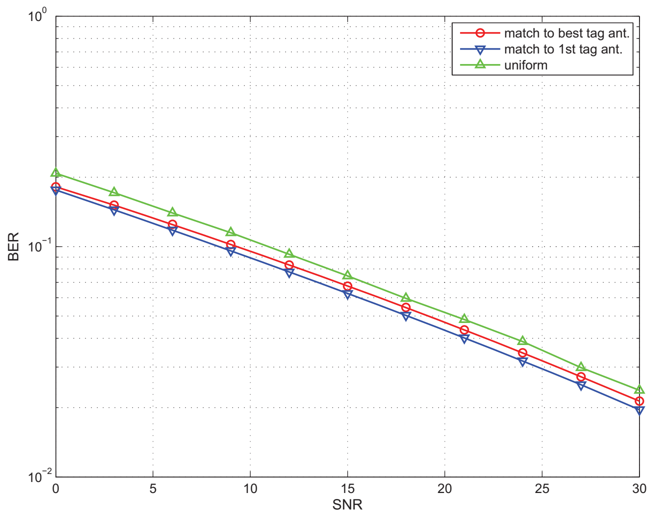


(c) for all other unmatched tag IDs

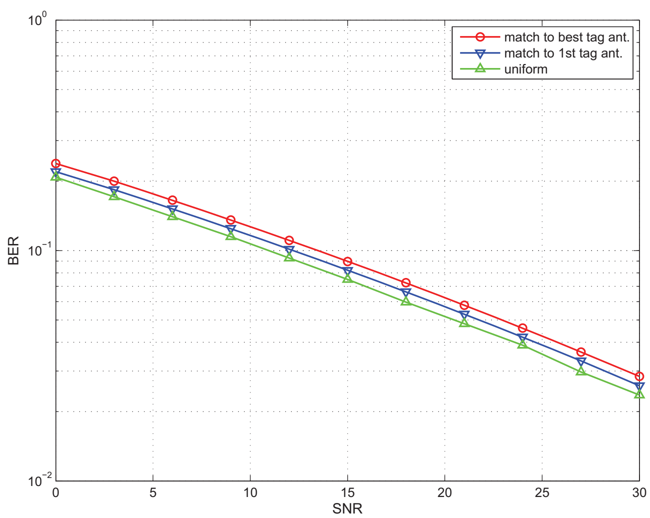
Figure 2. BER of the RFID MIMO system: $N_{\rm rd} = 4$, $N_{\rm tag} = 2$.



(a) for the optimally matched tag ID



(b) for all the tag IDs



(c) for all other unmatched tag IDs

Figure 3. BER of the RFID MIMO system: $N_{\rm rd} = 4$, $N_{\rm tag} = 4$.

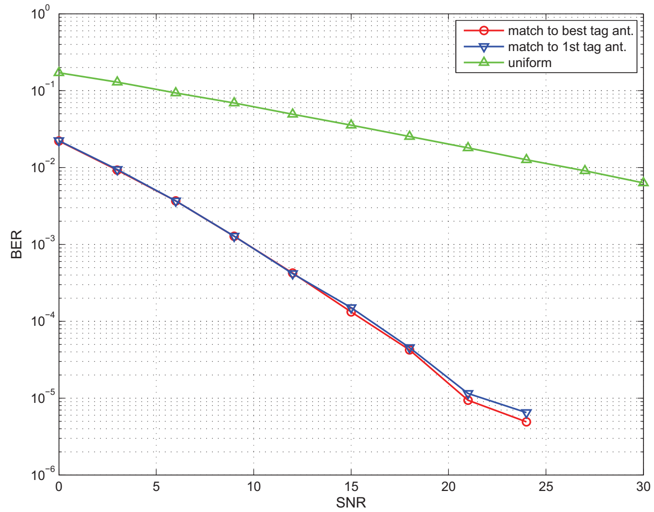


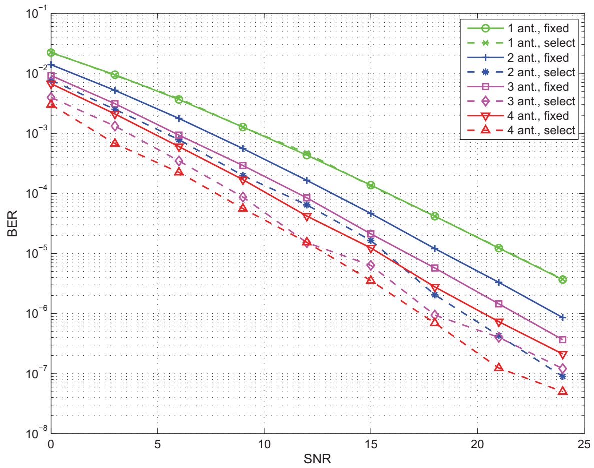
Figure 4. BER of the RFID MIMO system: $N_{\rm rd} = 4$, $N_{\rm tag} = 1$.

$N_{\rm tag}$	uniform	match to 1st tag	match to best tag
1	2.5×10^{-2}	4.2×10^{-5}	4.2×10^{-5}
2	1.9×10^{-3}	1.2×10^{-5}	2.1×10^{-6}
3	2.3×10^{-4}	5.7×10^{-6}	9.5×10^{-7}
4	4.2×10^{-5}	2.8×10^{-6}	7.0×10^{-7}

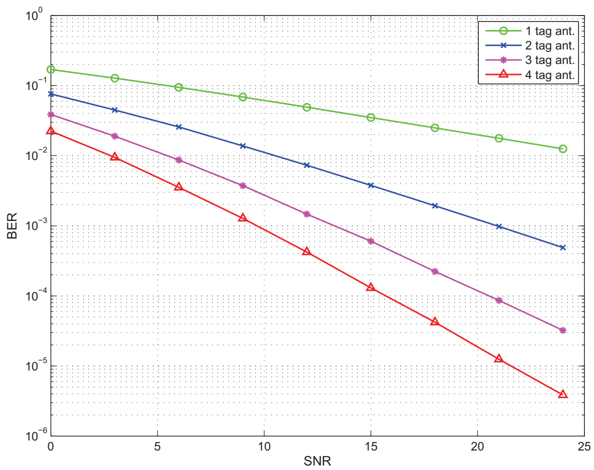
Table I
BER COMPARISON FOR A FIXED SNR AND DIFFERENT SYSTEM CONFIGURATION. SNR=18 DB, AND $N_{\rm rd} = 4$.

for the second case, where only one data symbol is transmitted across the multiple antennas at the tag in one time slot. In the figure, the legend "N ant." means that N (=1,2,3,4) antennas are equipped at the tag. The legend "fixed" means that the transmit signal at the reader is spatially matched to the channel corresponding to the first antenna at the tag, while the legend "select" means that the transmit signal at the reader is spatially matched to the best channel corresponding to the selected antenna at the tag. It can be seen that for a given number of antennas at the tag, to design the transmit signal at the reader with spatial matching to the best antennas at the tag gives about 2.5 dB gain in the SNR, compared to the case of being spatially matched to a fixed antenna at the tag. The more the antennas at the tag, the better the BER performance of the system. In the case of a single antenna at the tag, both policies produce the same BER performance.

Table I shows the BER comparison for a fixed SNR (18 dB) and different system configuration. It can be seen that, compared to the uniform transmit policy, the spatial matching transmit policy improves considerably the BER of the system.



(a) spatial matching transmission



(b) uniform transmission

Figure 5. BER of the RFID MIMO system. A single data symbol is transmitted across the multiple antennas at the tag in one time slot. $N_{\rm rd} = 4$, $N_{\rm tag} = 1, 2, 3$, or 4

V. Concluding Remarks

In this paper, we have discussed the reader's transmit signal design problem for RFID MIMO systems. First a mathematical model for this kind of system is developed from the viewpoint of signal processing, which makes it easy to design the transmit signals for both readers and tags and to decode the tag's ID. Two spatial matching transmission schemes, namely matched to a fixed antenna at the tag or matched to a selected antenna at the tag, for the reader's signals are proposed. Simulation results are provided, which illustrate that the proposed approaches can greatly improve the BER performance of RFID MIMO systems, compared to the uniform transmission policy.

In many application environments, the reader should recognize a large amount tags in a short time. This problem is challenging. The approach developed in this paper provides a possible solution for this problem. If the signals coming from all the tags, no matter whether the tags are equipped with multiple antennas or a single antenna each, are considered simultaneously, then we have an equivalent RFID MIMO systems. It can be easily seen that the first transmission way for the tag investigated in Section IV can be straightforwardly applied to this scenario.

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