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Transmit Diversity and Spatial Multiplexing for RF Links Using Modulated Backscatter

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ABSTRACT

A new multi-antenna or multiple-input-multiple-output (MIMO) configuration is introduced for RF modulated backscatter in a multipath environment. RF modulated backscatter is used by semipassive RF tags to transmit without a power amplifier, and is therefore appropriate for applications with extreme power constraints such as sensor communications, electronic shelf tags, electronic toll collection, and container identification. Channel information is used by the interrogator transmitter to provide transmit diversity. Multiple reflection antennas are used by the RF tags to reflect according to different data streams. Multiple interrogator receiver antennas provide multi-stream detection capability. Simulations show that range can be extended by a factor of four or more in the pure diversity configuration and that backscatter link capacity can be increased by a factor of ten or more in the spatial multiplexing configuration.

1. INTRODUCTION

RF modulated backscatter is the transmission technology used for the long-range variety of RF tags. Transmitters that use RF modulated backscatter can have extremely long battery lives because they have no power amplifier. However, links that use RF modulated backscatter are much weaker and have deeper fades than links with active transmitters, and therefore RF tag applications have been limited to ranges of 10s of meters [1] and data rates of up to 100kbit/s [2]. Their applications include sensors, inventory control, shipping container identification, electronic shelf tags, and automatic vehicle toll collection [1]. In this paper, we show how transmit diversity and spatial multiplexing can be applied to this kind of link to dramatically increase the range and data rates.

To read a RF tag that uses modulated backscatter, an interrogator illuminates the tag with an unmodulated carrier, as shown in Figure 1. The antenna terminals on the tag are switched between open and closed states, thereby modulating the reflection coefficient of the antenna. Switching the reflection coefficient creates a reflected signal that is amplitude-modulated. The interrogator receiver demodulates only the sidebands of the reflected signal [3].

Spatial diversity can be achieved through the use of multiple antennas at either the interrogator transmitter or the interrogator receiver, or at both. In our proposed scheme, the interrogator transmitter is assumed to know the modulated backscatter matrix

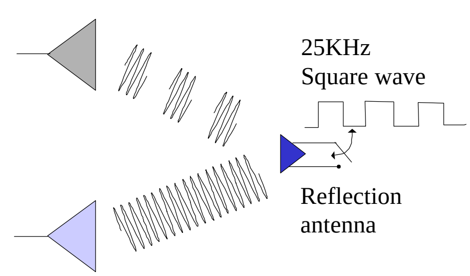

Figure 1. Modulated backscatter.

channel between interrogator transmit antennas and interrogator receive antennas. In practice, providing this channel information should be easier than for traditional links with active transmitters because all interrogator antennas can be on the same platform and the information can be conveyed over wire.

In addition, each tag can have more than one reflection antenna, as shown in Figure 2. In a pure diversity configuration, all the reflection antennas share the same baseband modulation waveform. Multiple reflection antennas modulated this way only serve to increase the average power of the reflected signal and combat shadowing; they provide no diversity gain. However, multiple reflection antennas or groups of them can be modulated with different data streams to provide spatial multiplexing, as shown in Figure 2. This is like BLAST [4], but the difference is that in BLAST, the transmitters are active and all transmit the same power, while for modulated backscatter, the powers reflected off different tags are functions of the interrogator transmit weights and the matrix channel between the interrogator transmitter and the tag antenna array. Since it is convenient for the interrogator transmit array to communicate with the interrogator receive array, we propose to use channel information to enhance the capacity of the modulated backscatter MIMO link.

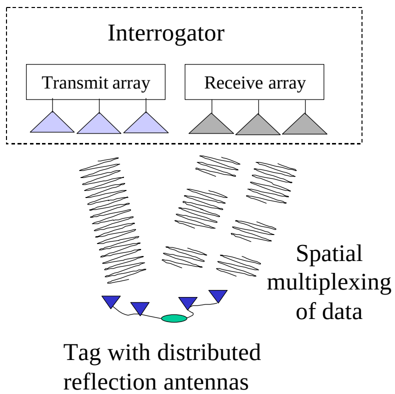

Figure 2. Modulated backscatter with transmit diversity and spatial multiplexing.

2. CHANNEL MODEL

Let the M, L and N denote the numbers of interrogator transmit antennas, reflection antennas, and interrogator receiver antennas. Let the M-element row vector **x** denote the weights on the interrogator transmitter, normalized to unit magnitude. Let g_{ij} be the complex amplitude path gain from the *i*th interrogator transmit antenna to the *j*th reflection antenna, and let the M by L matrix of these gains be **G**. Let the complex amplitude path gain from the *j*th reflection antenna to the *k*th interrogator receiver antenna be denoted by h_{jk}, and let the L by N matrix of these gains be **H**. The elements of **G** and **H** are normalized to unit average energy. Let $\mathbf{w}_j$ be the N-element, unit norm, row vector of interrogator receive weights corresponding to the *j*th reflection antenna. Then the output of the interrogator receiver combiner and filter matched to the symbol waveform is

$$z_j = \mathbf{xGBHw}'_j + \mathbf{nw}'_j \, , \qquad (1)$$

where $\mathbf{B} = \mathrm{diag}[b_1, b_2, \ldots, b_L]$ is the vector of transmitted unit energy, binary, on-off-keyed (OOK) symbols transmitted from each reflection antenna and **n** is a noise vector of complex Gaussian elements, each with average power $1/r$. Here r is the average SNR in one interrogator receiver if all of the power is transmitted through one interrogator transmit antenna and if there is only one tag antenna. The reflection coefficients of the tag antennas, the path losses, and any other losses are all absorbed by the **G** and **H** matrices. For a pure diversity configuration, only one bit, *b*, is transmitted in a symbol period, there is only one combiner in the interrogator receiver, and its output is

$$z = b\mathbf{xGHw}' + n \, . \qquad (2)$$

We evaluate our diversity and spatial multiplexing solutions through computer simulation using a statistical flat-fading channel model. Small-scale fading statistics for $|g_{11}\, h_{11}|$ when M=N=L=1 have recently been measured in a laboratory environment [5]. A sample measured cumulative distribution function (CDF) is shown in Figure 3. The measured CDF for a line-of-sight (LOS) environment is observed to fit closely to that of a "product Rician" random variable (RV). This RV is the product of two independent Rician RVs, both with the same *K* factor of -10 dB. The deep fades are observed to be more frequent than lognormal and Rayleigh, making this a promising application for diversity techniques.

Therefore, we model each g_{ij} and h_{jk} independently as $A\exp(j2pu) + s\,(X_r + jX_i)$, where X_r and X_i are iid Gaussian, with zero mean and unit variance, and u is an independent uniform RV distributed over [0,1]. A and s are chosen to yield a desired Rician *K* factor, as well as an overall unit average power. The *K* factor, $K=A^2/(2s^2)$, is the ratio of the power of the non- random component to the average power of the random compo-

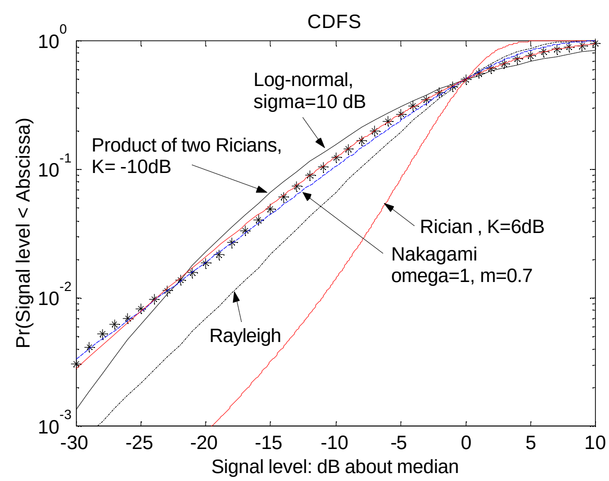

Figure 3. Cumulative distribution function (CDF) of measured small-scale fading plotted with several other CDFs.

nent. We multiply *A* by a random phase factor to account for the fact that the reflection antennas are randomly placed in a local area and cannot control how their reflections combine at the interrogator receiver antennas.

3. SPATIAL DIVERSITY

The optimal transmit and receive weight vectors in (2) can be found from the singular value decomposition of the matrix product **GH** [6]. Then, the optimal **x** is the conjugate transpose (CT) of the "largest" left singular vector of **GH**, that is, the left singular vector corresponding to the largest singular value, $s_{\max}$. **w** is the CT of the largest right singular vector of **GH**. The post-combiner signal power is $s^2_{\max}$. Since the average received signal power in the single-input single-output (SISO) configuration is unity, the average of $s^2_{\max}$ is also the SNR improvement from diversity combining. Because the interrogator transmitter exploits channel information, there is no power-splitting penalty for diversity at the interrogator transmitter. The probability of bit error for OOK, for a given channel realization, is [7]

$$P_{error} = \frac{1}{2} erfc\left(\sqrt{\frac{s_{\max}^{2} r}{2}}\right). \qquad (3)$$

Because of the two-way nature of the backscatter link, the range can be doubled while maintaining the same bit error rate (BER) performance for every 12 dB of SNR improvement [3].

Figures 4 and 5 show CDFs for the log base 10 of the average bit error rates, $\log_{10} E_{s_{\max}}(P_{error})$, where the average is over the different channel realizations. Figure 4 is for the case when there is only one reflection antenna, and the number of elements in each of the interrogator arrays is either 1, 2, 4, or 8. At the BER of 10E-2, the required transmit power is reduced by about 24 dB with four antenna elements in each interrogator array compared to the M=N=L=1 case. This corresponds to a factor of 4-range extension.

In Figure 5, the number of elements in each interrogator array is held constant at 4 and the number of reflection antennas is varied. Increasing the number of reflection antennas simply increases the total reflecting area. The average power is increased with a very small increase in the diversity gain; this is apparent from the fact that the slopes on the BER curves at high SNR change very little. At the BER of 10E-2, each doubling of the number of reflection antennas yields about a 3dB reduction in the required transmit power.

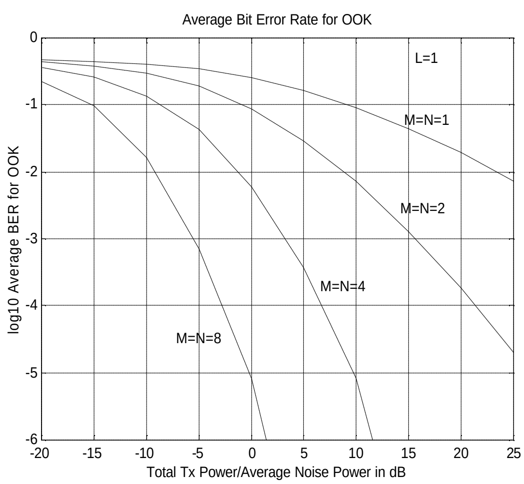

Figure 4. Log of the average probability of bit error with one reflection antenna.

4. SPATIAL MULTIPLEXING

In this section, we consider modulating each reflection antenna with a different data stream, as in equation (1). Any multiuser detection scheme can be employed to detect the L data streams in the interrogator receiver. The theoretical capacity between two arrays where an independent data stream is transmitted on each transmit antenna element is well known to be

$$C = \log_2\left(\det\left[\mathbf{I} + r\mathbf{H}'\mathbf{P}\mathbf{H}\right]\right), \qquad (4)$$

where $\mathbf{P} = \mathbf{T}'\mathbf{T}$ is the diagonal autocorrelation matrix of the transmitted signals, and $\mathbf{T}$ is the diagonal matrix of complex amplitudes. For modulated backscatter, and given $\mathbf{G}$, the ith element of $\mathbf{T}$ is $\mathbf{x}\mathbf{g}_i$, where $\mathbf{g}_i$ is the ith column of $\mathbf{G}$. Our goal in this section is to find solutions for $\mathbf{x}$, assuming channel knowledge at the interrogator transmitter.

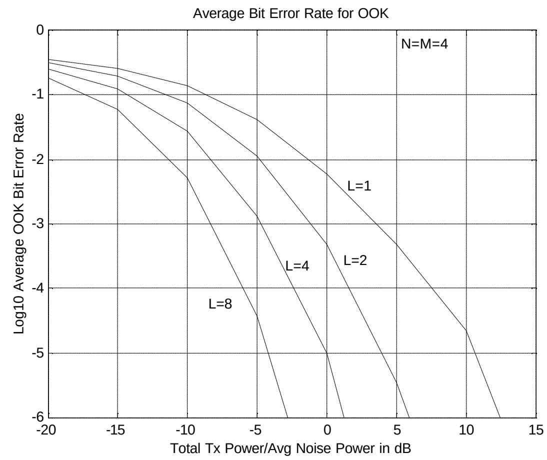

Figure 5. Log of the average BER with 4 elements in each interrogator array.

We consider six solutions: the optimal mean squared error (MSE) solution, four suboptimal, but simpler solutions, and one non-adaptive solution for comparison.

We take an iterative approach to finding the optimal MSE solution. Let $\mathbf{W}$ be the matrix of receive weight vectors. The MSE may be expressed

$$MSE = \sum_{i=1}^{L} a_{ii}\mathbf{x}\mathbf{g}_i\mathbf{g}_i'\mathbf{x}' - b_{ii}\mathbf{x}\mathbf{g}_i - b_{ii}^{*}\mathbf{g}_i'\mathbf{x}' + \text{constant}, \qquad (5)$$

where a_{ii} is the ith diagonal element of $\mathbf{H}\mathbf{W}'\mathbf{W}\mathbf{H}'$, and b_{ii} is the ith diagonal element of $\mathbf{W}\mathbf{H}'$. We add $l(\mathbf{x}\mathbf{x}'-1)$, where λ is the Lagrange multiplier, to (5) to represent a unity constraint on the total interrogator transmit power. The optimal $\mathbf{x}$ is

$$\mathbf{x} = \sum_{i=1}^{L} b_{ii}^{*}\mathbf{g}_i'\left(\sum_{i=1}^{L} a_{ii}\mathbf{g}_i\mathbf{g}_i' + l\mathbf{I}\right)^{-1}. \qquad (6)$$

Given a transmit weight vector $\mathbf{x}$, the optimal MSE receiver weight matrix $\mathbf{W}$ is well known to be

$$\mathbf{W} = \mathbf{T}\mathbf{H}\left(\mathbf{H}'\mathbf{T}'\mathbf{T}\mathbf{H} + r^{-1}\mathbf{I}\right)^{-1}. \qquad (7)$$

While this expression for $\mathbf{W}$ could be substituted back into (5), and the optimum $\mathbf{x}$ found directly, we compute $\mathbf{W}$ and $\mathbf{x}$ iteratively until their values converge.

In the first suboptimal solution, $\mathbf{x}_G$ is the CT of the largest left singular vector of **G**; this solution produces the most reflected power. The second suboptimal solution, $\mathbf{x}_{norm}$, is the CT of the largest left singular vector of a matrix made from **G** by normalizing each of its columns to have unit norm. Some reflection antennas have a better connection to the interrogator receiver than others, as indicated by the norms of the rows of **H**. Therefore, in the third suboptimal approach, the transmit weight vector is the CT of the largest left singular vector of a matrix made from **G** by weighting each of its columns with the norm of the corresponding row of **H**. The fourth suboptimal approach uses the optimum diversity solution from Section 3. The non-adaptive solution simply uses equal weights and is equivalent to the single transmitter (M=1) case.

The CDFs of capacity for these different solutions are shown in Figure 6. With the exception of the equal weights case, we observe little difference between the various solutions, with "G with columns normalized" (GWCN) and MMSE solutions giving the highest capacity. As a reference, the median capacity for M=L=N=1 (no diversity and no spatial multiplexing) at SNR of 10 dB is a little greater than 2 b/s/Hz. M=4 yields at least 2 more b/s/Hz from transmit diversity. Then L=N=4 multiplies the result by 4, so the best median capacity of 20 b/s/Hz can be justified.

For each transmit weight vector solution, we computed the MMSE receive vector. CDFs for the resulting MMSEs are shown in Figure 7, confirming that our optimal MMSE solution for the transmit weights yields lower MMSE than the others. The GWCN solution yielded an MMSE within 1 dB of the optimum. The optimal MMSE transmit weight vector did not always yield the highest capacity. At 25 dB, for M=L=N=4, the median capacity of the GWCN solution exceeded that of the optimal MMSE solution.

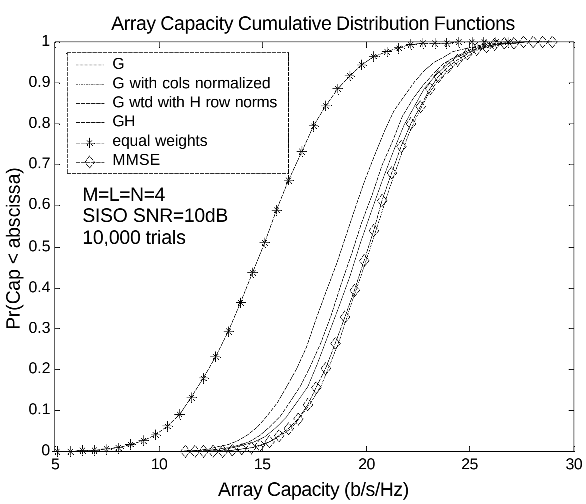

Figure 6. Array capacity in bits/sec/Hz when there is fourth order transmit diversity, four reflection antennas and four receiver antennas.

5. CONCLUSION

We propose MIMO techniques for RF links employing modulated backscatter. We assume that the interrogator transmitter array knows the matrix channel; this may be easier for backscatter links because the interrogator tranmsitter and receiver can have a wired connection. We find that the enormous gains that MIMO techniques provide to links with active transmitters can also be achieved for links with RF modulated backscatter.

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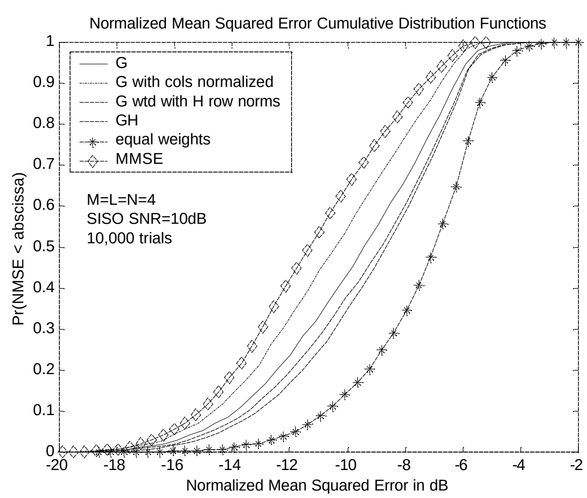

Figure 7. MMSE for each transmit weight solution.