Spatial Modulation – A New Low Complexity Spectral Efficiency Enhancing Technique

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Abstract— **The multiplexing gain of multiple antenna transmission strongly depends on transmit and receive antenna spacing, transmit antenna synchronization, and the algorithm used to eliminate interchannel interference (ICI) at the receiver. In this paper, a new transmission approach, called *spatial modulation*, that entirely avoids ICI and requires no synchronization between the transmitting antennas while maintaining high spectral efficiency is presented. A block of information bits is mapped into a constellation point in the signal and the spatial domain, i.e. into the location of a particular antenna. The receiver estimates the transmitted signal and the transmit antenna number and uses the two information to de-map the block of information bits. For this purpose, a novel transmit antenna number detection algorithm called *iterative-maximum ratio combining (i-MRC)* is presented. Spatial modulation is used to transmit different number of information bits and i-MRC is used to estimate both the transmitted signal and the transmit antenna number. The results are compared to ideal V-BLAST (Vertical-Bell Lab Layered Space-Time) and to MRC. Spatial modulation outperforms MRC. The (bit-error-ratio) BER performance and the achieved spectral efficiency is comparable to V-BLAST. However, spatial modulation results in a vast reduction in receiver complexity.**

I. Introduction

The need to improve the spectral efficiency and reliability of radio communication is driven by the ever increasing requirement for higher data rates and improved QoS (Quality of Service) across wireless links. Higher data rate and better spectral efficiency are of paramount importance in next generation cellular communication. MIMO (multiple input multiple output) technology is one solution to attain this by transmitting multiple data streams from multiple antennas [1]. However, the capacity gain results from MIMO transmission depends strongly on transmit and receive antenna spacing [2], [3], transmit antenna synchronization [4], [5], and the used algorithm to reduce the interchannel interference (ICI) at the receiver input. Copious ICI reduction algorithms are reported in literature. The proposed Bell Labs Layered Space-Time Architecture (BLAST) [6] is one of the most promising MIMO detection algorithms. In its most basic form known as vertical (V)-BLAST [7], multiple transmitted data streams are separated and detected successively using a combination of array processing (nulling) and interference cancellation techniques. It was demonstrated that with the V-BLAST algorithm spectral efficiencies of $20 - 40$ bps/Hz can be achieved in an indoor rich scattering propagation environment assuming a practical SNR range, and bit-error performance respectively [7]. The high spectral efficiencies stem from parallel signal transmission resulting in a multiplexing gain. Other multiple antenna techniques employ, for example, space-time coding (STC) techniques in order to increase the SNR at the receiver by exploitation of spatial diversity [8]. In this case the system improvement results from a diversity gain.

An alternative transmission approach that entirely avoids ICI at the receiver input was proposed in [9], [10] for BPSK and QPSK transmission respectively. The idea is to compress a block of N_t symbols into a single symbol prior to transmission, where N_t indicates the number of transmit antennas. Information is retained by an algorithm that maps this single symbol to one, and only one, of the N_t antennas. The task of the receiver is twofold: First, to estimate the single symbol, and second, to detect the respective antenna number from which the symbol is transmitted. By combining both information and by carrying out the inverse encoding operation, the receiver is able to retrieve the entire block of N_t symbols. Thereby, multiplexing gain is achieved, but ICI in the MIMO transmission is completely avoided. However, the scheme in [10] suffers from a loss in spectral efficiency as compared to V-BLAST due to the use of parity symbols. Moreover, a general solution for different modulation schemes is not provided in [10].

The proposed concept solves this problem in a novel fashion. Traditionally, modulation techniques such as BPSK (binary phase shift keying), QPSK (quadrature phase shift keying), 8PSK, 16QAM (quadrature amplitude modulation), etc. map a fixed number of information bits into one symbol. Each symbol represents a constellation point in the complex, two dimensional signal plane. In the following this is referred to as *signal* modulation. In this paper, a novel approach is proposed in which this two dimensional plane is extended to a third dimension - the spatial dimension. In the following this is referred to as *spatial* modulation. It is demonstrated that this new approach will result in a very flexible mechanism which is able to achieve high spectral efficiency and very low receiver complexity, and that is ideally suited for high speed uplink transmission.

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The idea of using the transmit antenna number as an additional source of information is utilized in spatial modulation. The number of information bits that can be transmitted using spatial modulation depends on the used constellation diagram and the given number of transmit antennas. For instance, six information bits can be mapped into 32QAM and two transmit antennas. Alternatively, if the channel and interference environment do not allow the use of 32QAM, the same spectral efficiency can be achieved with 16QAM and four transmit antennas, etc..

In view of the fact that information is not only included in the transmitted symbol but also in the actual physical location of the antenna, estimation of the transmit antenna number is of key importance. In this paper, an innovative transmit antenna number detection algorithm, called *iterative-maximum ratio combining (i-MRC)* is presented. The i-MRC algorithm is based on the fact that only one antenna transmit at a time. The antenna number may change at the subsequent transmission instants, but at any given time only a single transmit antenna is transmitting. The channel vectors between each transmit antenna and the number of receive antennas are considered separately at the receiver. The receiver iteratively computes the MRC results between the channel paths from each transmit antenna to the corresponding receive antennas. Assuming full knowledge of the channel at the receiver, the receiver chooses the transmit antenna number which gives highest correlation.

In addition to eliminating ICI at the receiver, spatial modulation produces no correlation between the transmit antennas and it requires no synchronization between them. In general, 1/2 wavelength spacing can achieve uncorrelated fading but this is affected by factors such as the proximity to the human body and other objects. On the other hand, lack of synchronization is shown to have a major effect on system performance [4], [5]. Furthermore, in spatial modulation, the symbol duration is unchanged while the transmitted symbol carries a higher number of information bits (note that the distance between the signal constellation points is not altered) due to the novel extension of modulation to the spatial domain. As a consequence, an improvement in spectrum efficiency is obtained.

The rest of the paper is organized as follows: In Section II, the spatial modulation system model is presented. In Section III, the i-MRC antenna number detection algorithm is presented. Simulation results and a receiver complexity comparison are shown in Section IV. Finally, conclusions are provided in Section V.

II. SYSTEM MODEL

Throughout the paper, the following notations and assumptions are used. Bold and small letters **'a'** denote vectors. Bold and capital letters **'A'** denote matrices. The notations, $(\cdot)^*, (\cdot)^+, (\cdot)^H$, and $(\cdot)^T$ denote conjugate, pseudoinverse, Hermitian, and transpose, of a matrix or a vector respectively, and $(\cdot)^{-1}$ denotes the inverse of a matrix. $h_{\nu,\tau}$ is the channel gain between transmit antenna τ and receive antenna ν. N_r is the number of receive antennas. Finally, for MQAM modulation, $m = \log_2(M)$ is the number of bits/symbol. The spatial modulation system model is shown in Fig. 1. $\mathbf{q}(k)$ is a vector of n bits to be transmitted. The binary vector is mapped into another vector $\mathbf{x}(k)$ of size N_t such that only one element in the resulting vector is different from zero. Symbol number ℓ in the resulting vector $\mathbf{x}(k)$ is x_ℓ, where ℓ is the mapped transmit antenna number $\ell \in [1 : N_t]$. The symbol x_ℓ is transmitted from the antenna number ℓ over the MIMO channel, $\mathbf{H}(k)$. $\mathbf{H}(k)$ can be written as a set of vectors where each vector corresponds to the channel path gains between transmit antenna ν and the receive antennas as follows:

$$\mathbf{H} = \begin{bmatrix} \mathbf{h}_1 & \mathbf{h}_2 & \cdots & \mathbf{h}_{N_t} \end{bmatrix} \tag{1}$$

where:

$$\mathbf{h}_\nu = \begin{bmatrix} h_{1,\nu} & h_{2,\nu} & \cdots & h_{N_r,\nu} \end{bmatrix}^T \tag{2}$$

The received vector is then given by $\mathbf{y}(k) = \mathbf{h}_{(\nu=\ell)} x_\ell + \mathbf{w}(k)$; where $\mathbf{w}(k)$ is the additive white Gaussian noise vector.

The number of transmitted information bits, n, can be adjusted in two different and independent ways – either by changing the signal modulation and/or changing the spatial modulation. For example, three bits per symbol could be send from four transmit antennas using BPSK modulation as shown in Fig. 2. Alternatively, using two transmit antennas instead of four, three bits could be send if the modulation technique is changed to 4QAM as shown in Fig. 2. Similarly, in order to transmit four bits, BPSK modulation and eight antennas can be used or 4QAM modulation and four transmit antennas. The same spectral efficiency can be achieve if two antennas and 8QAM are used.

In general, the number of bits that can be transmitted using spatial modulation is given as follows:

$$n = \log_2(N_t) + m \tag{3}$$

III. TRANSMIT ANTENNA NUMBER ESTIMATION

With spatial modulation data is encoded in an information symbol and an antenna number. Hence, estimation of the transmit antenna number is an important task. In the following, a novel antenna number detection algorithm is presented.

The received vector $\mathbf{y}(k)$ is iteratively multiplied by the channel path gains, which are assumed to be known at the receiver, in order to estimate both: the transmitted symbol and the transmit antenna number:

$$\begin{aligned} g_j &= \mathbf{h}_j^H \mathbf{y}, \quad \text{For } j = 1 : N_t && (4) \\ \mathbf{g} &= \begin{bmatrix} g_1 & g_2 & \cdots & g_{N_t} \end{bmatrix}^T && (5) \\ \tilde{\ell} &= \arg\max_j |\mathbf{g}| && (6) \\ \tilde{x}_\ell &= Q(\mathbf{g}_{(j=\tilde{\ell})}) && (7) \end{aligned}$$

where $Q(\cdot)$ is the constellation quantization (slicing) function.

Assuming correct estimates for $\tilde{\ell}$ and $\tilde{x}_\ell$, the receiver can straightforwardly de-map the original information bits.

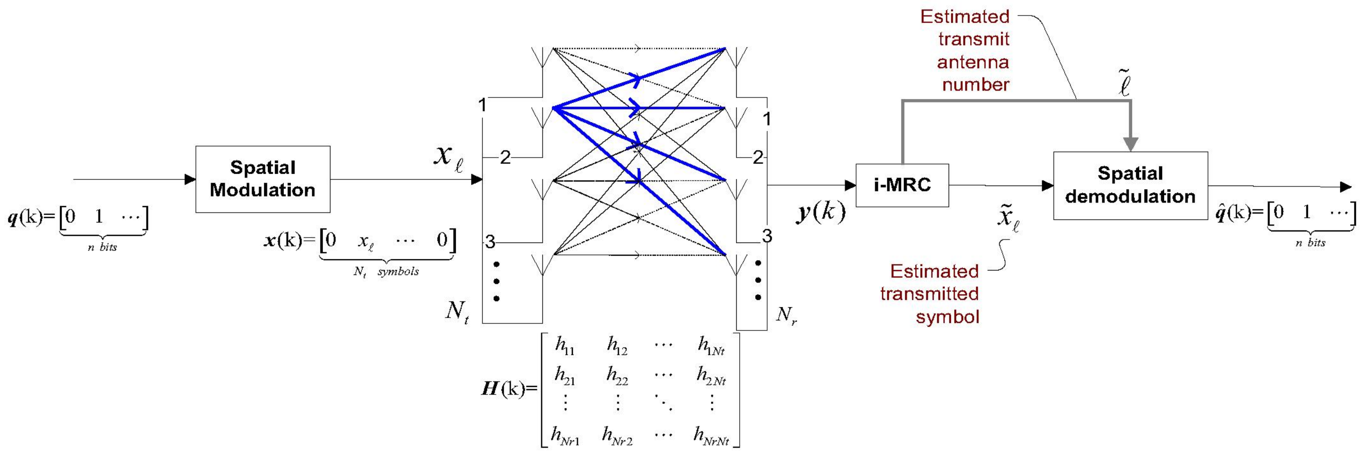

Fig. 1. Spatial Modulation System Model

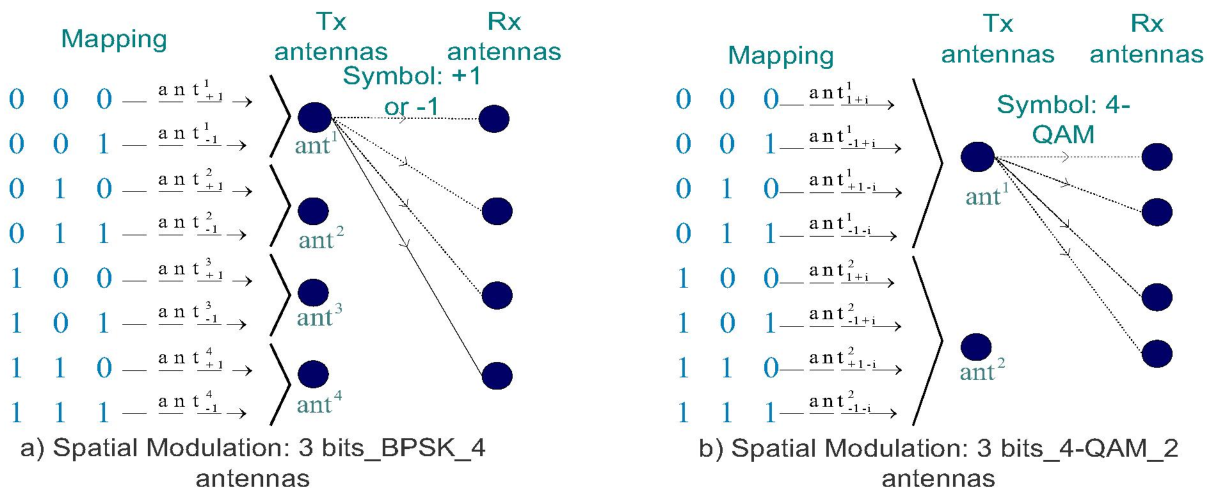

Fig. 2. Spatial Modulation: 3bits transmission using BPSK and four transmit antennas, or, 4QAM and two transmit antennas

A. Example: 3 bits spatial modulation transmission and detection using 2x4 antenna configuration and 4QAM transmission

The mapping table for 3 bits transmission using 4QAM signal modulation and 2x4 MIMO antenna configuration is shown in Fig. 2.

Assume the following sequence of bits to be transmitted, $\mathbf{q}(k) = [0, 1, 1]$. Mapping this to a 4QAM symbol and two transmit antennas results in $\mathbf{x}(k) = [-1 - i, 0]^T$, where i is the imaginary number, $i = \sqrt{-1}$. The vector $\mathbf{x}(k)$ is transmitted over the 2x4 MIMO channel $\mathbf{H}(k)$. Note that only antenna number one will be transmitting the symbol x_ℓ and antenna number two will be transmitting zero energy. For example, assume the following channel matrix and noise free transmission:

$$\mathbf{H}(k) = \begin{pmatrix} -0.5377 - 0.1229i & -0.6175 + 0.1516i \\ -0.5450 - 0.0964i & -0.3271 - 0.0006i \\ 0.4624 - 0.2680i & 0.2058 + 0.3171i \\ 0.2854 - 0.1493i & -0.5190 + 0.2767i \end{pmatrix}$$

Then, the received vector at the receiver input equals $\mathbf{y}(k) = [0.4149 + 0.6606i, 0.4486 + 0.6415i, -0.7304 - 0.1944i, -0.4348 - 0.1361i]^T$.

The i-MRC detection algorithm is considered in the following. The channel is assumed to be known at the receiver. applying the i-MRC detection algorithm to the received vector $\mathbf{y}(k)$ results in $\mathbf{g} = [-1.0000 - 1.0000i, -0.3271 - 0.2978i]$. Then, the antenna number can be estimated by computing eqn. (6) and results in $\tilde{\ell} = 1$. Similarly, the transmitted symbol can be estimated by computing eqn. (7) and results in $\tilde{x}_\ell = -1 - i$. Using the respective look-up table in Fig. 2, the transmitted 3-bit sequence can be de-mapped into $\hat{\mathbf{q}}(k) = [0, 1, 1]$, which exactly corresponds to the transmitted bits.

The estimation of the transmit antenna number is based on the cross correlation between different channel paths. Therefore, like in other spatial multiplexing techniques, the performance of the algorithm is dependent on the channel correlation. However, with the proposed new technique, the correlation only depends on the characteristics of the channel and not on the spacing between the transmit antennas since only a single antenna transmit at any given time. This is deemed an important feature – especially for uplink transmission.

IV. Results

In the simulation a flat Rayleigh fading channel is assumed with additive white Gaussian noise (AWGN). The receiver is assumed to have full channel knowledge. The receive antennas are assumed to be separated wide enough to avoid correlation. The total transmit power, P, is the same for all transmission and the SNR at each receiver input is given by $\frac{P}{\sigma^2}$, where σ^2 is the noise power. For V-BLAST transmission, the transmit antennas are assumed to be synchronized and separated wide enough to avoid correlation. Finally, the SNR is assumed to be known at the receiver when using the MMSE (minimum mean square estimation) algorithm for V-BLAST detection.

A. Three bits transmission

The BER (bit-error-ratio) of 4x4 BPSK and 2x4 4QAM spatial modulation is plotted in Fig. 3. The 3x4 BPSK MMSE V-BLAST and 1x4 8QAM MRC results are plotted in the same figure. 4x4 BPSK spatial modulation performs nearly the same as the 1x8 8QAM MRC and 2x4 4QAM spatial modulation performs almost the same as 3x4 BPSK MMSE V-BLAST. 4x4 BPSK spatial modulation shows a performance degradation of 2 dB as compared to 2x4 4QAM spatial modulation and 3x4 BPSK MMSE V-BLAST.

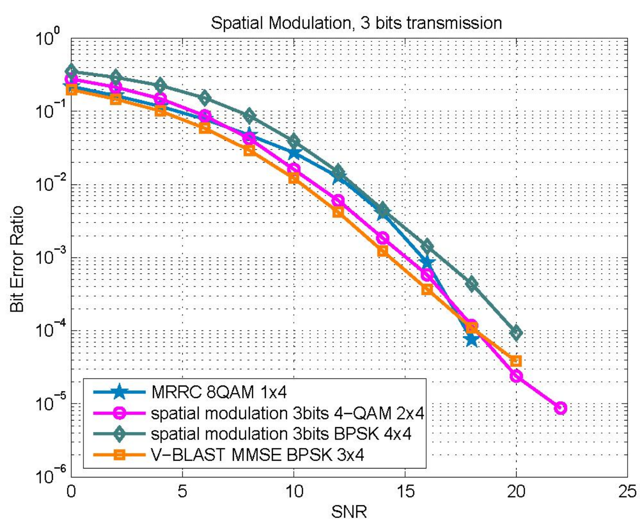

Fig. 3. Three bits transmission using spatial modulation, V-BLAST, and MRC

B. Five bits transmission

Five bits transmission BER using 4x4 8QAM and 2x4 16QAM spatial modulation and 1x4 32QAM MRC are plotted in Fig. 4. It is difficult to directly compare this constellation to V-BLAST as 5-bit transmission is not possible. Therefore, the V-BLAST transmission with six bits is chosen, i.e., 2x4 8QAM MMSE. The results are plotted in Fig. 4. Spatial modulation and V-BLAST perform virtually the same. In addition, 2x4 16QAM and the 4x4 8QAM spatial modulation results also match very closely. The spatial modulation technique outperforms 1x4 32QAM MRC by about 4 dB.

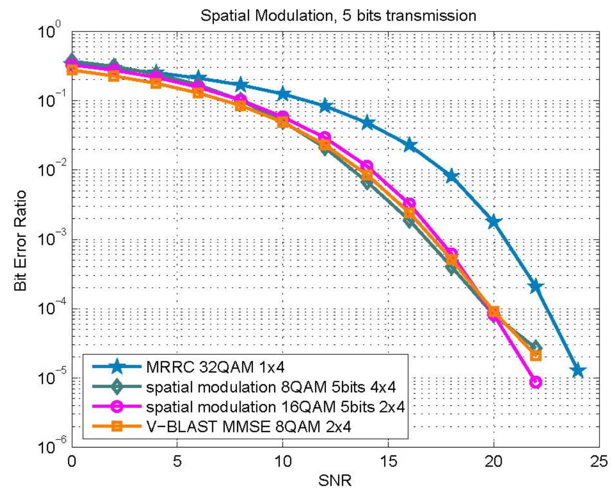

Fig. 4. Five bits transmission using spatial modulation and MRC

C. Six bits transmission

Fig. 5 shows the BER performance of spatial modulation 4x4 16QAM transmission and 2x4 32QAM transmission compared to 2x4 8QAM and 3x4 4QAM MMSE V-BLAST algorithm and to 1x4 64QAM MRC transmission. 4x4 16-QAM transmission and 2x4 8QAM V-BLAST transmission perform nearly the same. 3x4 4QAM MMSE V-BLAST transmission shows a degradation in performance at high SNR due to the presence of error propagation and the high ICI at the receiver. The new spatial modulation 4x4 16QAM transmission outperforms 1x4 64QAM MRC transmission by approximately 7 dB.

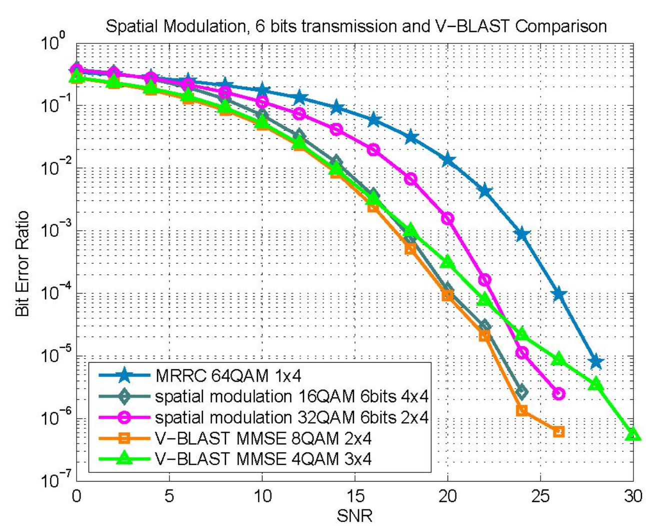

Fig. 5. Six bits transmission using spatial modulation, V-BLAST, and MRC

D. System Complexity Estimation

The system complexity of the discussed transmission techniques in this paper is considered in the following.

Consider only multiplication and addition of a complex numbers as an operation.

The MMSE criterion requires two matrix multiplications, one inversion and one addition. It is assumed that the matrix transposes are not computed explicitly. The first matrix multiplication requires $N_t^2 N_r$, the matrix addition requires N_t^2 and the matrix inverse needs $4N_t^3$ (using Gaussian Elimination) operations [11], [12]. The second matrix multiplication takes N_t^3 operations. Therefore, a total of $(5N_t^3 + N_r N_t^2 + N_t^2)$ complex operations are needed. For V-BLAST these steps are repeated for $i = 1 \ldots N_t$ [13]. This means that the MMSE is computed for deflated $\mathbf{H}$ but with decreasing dimensions of $(N_r \times (N_t - L)), L = 0 \ldots N_t - 1$. As a result, the total number of complex operations is given by:

$$\sum_{i=1}^{N_t} (5i^3 + N_r i^2 + i^2). \quad (8)$$

i-MRC requires $N_t N_r$ complex multiplications and $N_t(N_r - 1)$ complex additions. So, a total of:

$$[2N_t N_r - N_t] \quad (9)$$

complex operations are required.

In the following, let ξ be the number of complex operations. The receiver complexity comparisons between the spatial modulation and V-BLAST are shown in Table I for three bits transmission and in Table II for six bits transmission.

TABLE I

THREE BITS TRANSMISSION REVIVER COMPLEXITY COMPARISON

	V-BLAST	Spatial Modulation	
	MMSE	BPSK	4QAM
ξ	560	28	14

TABLE II

SIX BITS TRANSMISSION REVIVER COMPLEXITY COMPARISON

	8QAM V-BLAST	4QAM V-BLAST	Spatial Modulation	
	MMSE	MMSE	16QAM	32QAM
ξ	110	560	28	14

V. Conclusion

A novel spectral efficient multiple antenna transmission scheme that utilizes the spatial information in an innovative fashion has been presented. A new modulation scheme, called *spatial modulation*, maps multiple information bits into a single information symbol and into the physical location of the single transmitting antenna. Spatial modulation avoids ICI at the receiver input, produces no correlation between the transmit antennas and requires no synchronization between them. Moreover, spatial modulation does not suffer from the error propagation problem that exists in V-BLAST. In addition, a special transmit antenna number detection algorithm tailored for the new spatial modulation technique has been proposed. While the new spatial modulation technique shows almost the same BER performance for the same spectral efficiency as ideal V-BLAST, it results in a significant reduction in receiver complexity. In addition, only one RF (radio frequency) chain is required at the transmitter because at any given time only one antenna transmits. This means that the cost of the transmitter can be significantly reduced. Spatial modulation is expected to outperform V-BLAST under more realistic assumptions, i.e. taking into consideration transmit antenna correlation and frequency and antenna synchronization issues. This is subject to future research.

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