Published by :
http://www.ijert.org
International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 12 Issue 01, January-2023

The Performance of Virtual-MIMO using real-time Measurement Data with The Joint Transmit and Receive Design with Channel State Information.

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Abstract— **In this paper, based on 5GHz real-time indoor multi-input multi-output (MIMO) measurements, The joint transmit and receive design with channel state information (CSI), such that single and multi-beamforming, are investigated to study the performance of virtual multi-input multi-output (MIMO) over single-user MIMO system.**
However, to form a virtual MIMO multi-user system, the resources of two users are brought together. In order to achieve a low spatial correlation, two spaced antennas in the MS have been chosen and four spaced antennas elements in BS have been selected. Therefore, the resources of two users (U1 and U2) are brought together to form a 4x4 virtual MIMO multi-user system with the BS. The properties of the user_1 (U1) and user_2 (U2) will be analyzed and compared to those properties of virtual MIMO multi-user system formed by U1 and U2. In most cases, the maximum achievable rate is seen with virtual MIMO multi-user compared to single-user MIMO. So virtual MIMO multi-user is desirable for boosting system capacity than single-user MIMO.

Keywords— Virtual MIMO; Capacity; Beamforming.

I. Introduction

In wireless communication, the radio channel is affected by many distortions such as channel fading and signal-to-noise ratio variation [1], [2]. The signals will propagate by way of multipath before they reach the destination in different directions which is an undesirable phenomenon. To deal with this problem multi-antenna elements are adapted in the base station (BS) and mobile station (MS). The process of using multi-antenna elements in both of the BS and MS is called single-user multi-input multi-output (SU-MIMO). To achieve maximum capacity, SU-MIMO is used with a special post-precoding signal processing [3]. The goal of post-precoding signal processing techniques is to produce among of the multiple signals arrived at the receiver, one signal that has been originally transmitted by the transmitter. The signal processing technique used in this paper is the joint transmit and receive design with CSI.

The SU-MIMO exploits space dimension to improve wireless system capacity. It offers significant increases in data throughput and link range without additional bandwidth or increased transmit power. With the SU-MIMO the capacity is increased as the number of antenna is increased. However, if the antennas are much closer from each other's, the radio channel will be correlated which causes the capacity degradation. The reason is that, if the radio channels are full correlated, the SU-MIMO system will become like conventional single-input single-output (SISO) system. For that reason, the antennas must be paired in a suitable way in the users and the BS site in order to benefit from low correlation. That is to say, we need to put more space between antenna elements. For the proper set of antennas number in MS and BS terminal, it is better to use antennas selection techniques as indicated in [5, 6]. To exploit wider space between antenna elements, one approach is to use cooperative MIMO or V-MIMO system [7, 8]. With V-MIMO system, it can benefit wider space between antenna elements from users.

In many papers the outdoor measurements were performed using real-time MIMO channel measurements synchronously over multiple users to compare different precoding schemes. Contrary to this paper, the real-time MIMO channel measurements have been done at a center frequency of 5.25 GHz with a 100 MHz signal bandwidth. However, V-MIMO or multi-users MIMO system is formed by bringing together the resources of two users in order to compare different precoding schemes. The comparison is made also between V-MIMO and SU-MIMO.

The main focus of this paper is the evaluation of V-MIMO system performance in multi-user. So the question is that: Is it possible for two users to cooperate? The answer of that question is yes; two users can cooperate and share their resources because the cooperative MIMO has been already incorporated in some wireless standards, such as Wireless sensor networks [9, 10].

In this paper the performance of the V-MIMO over SU-MIMO is investigated by the joint transmit - receive beamforming using a real indoor data measurements performed in Helsinki, Finland.

The paper is structured as follows. Section 2 shows measurement system and campaigns. Section 3 presents the System model. Section 4 shows virtual MIMO system construction. Section 5 introduces the precoding schemes, and Section 6 draws the conclusions.

II. Measurement System and campaigns

The measurement campaign took place in the building of the Nokia Research Center (NRC) in Ruoholahti, Helsinki, Finland. The environments covered the following propagation scenarios: wide indoor areas, open office environments, office rooms connected by a corridor, and meeting rooms, see Fig. 1. The measurements were performed using 5.25 GHz carrier frequency with 100 MHz bandwidth. The BS consists of the radio channel sounder receiver unit, which was connected to a planar array with 32 dual-polarized elements, but for measurement only 12 dual polarized (vertical and horizontal polarizations) antenna elements was activated as shown in Fig. 2a. The user or the MS antenna prototype having four different dipole antennas were connected to the transmitter as shown in Fig. 2b. So the total number of the BS (Rx-receiver) was 24 and the total number of the MS (Tx-transmitter) was four. This results in 4 x 24 = 96 measured radio channels. In addition, the Tx-switching requires four additional channel guards to be present, therefore resulting in a channel number of 100 measured channels.

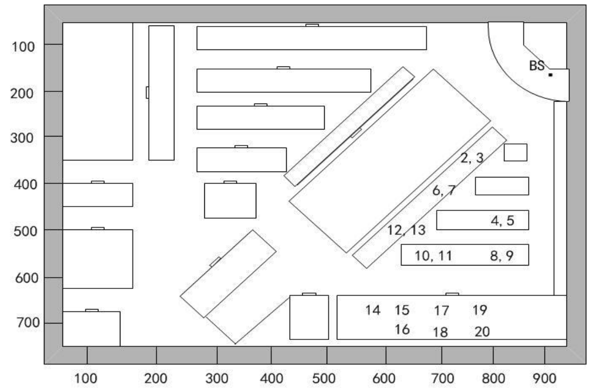

Fig. 1. Measurement locations in NRC, Helsinki, Finland. The numbers on figure show the mobile station locations (users).

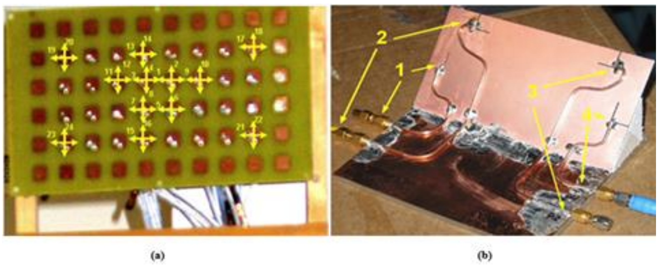

Fig. 2. Antennas elements. (a) The base station antenna array connected antenna elements are marked and shown with the corresponding Rx-antenna numbers. Each odd channel number (1, 3 …) was designated for a horizontally polarized input and each even channel number (2, 4 …) for a horizontally polarized input, respectively; (b) the mobile terminal antenna prototype used in the measurements. The antennas and the connectors are shown with the corresponding Tx-antenna numbers.

III. System Model

In this paper, assume the receiver signal at the BS is given by:

$$y = h_k x_k + \sum_{i \neq k} h_i x_i + n \qquad (1)$$

where h_k is channel, x_k is a transmit signal, n is a noise

Our purpose is to decode packet k from receiver signal. Therefore the receiver is to be decomposed to isolate the contribution packet k.

The term $\sum_{i \neq k} h_i x_i$ acts as an interference and is referred to us as inter-symbol interference (ISI).The system will becomes like a SIMO system with input x_k, channel h_k and an additive white Gaussian noise n if the ISI is suppressed. However the precoding techniques are used to suppress that inter-symbol interference (ISI) from receiver signal. And we consider the joint transmit and receive design with CSI precoding schemes in this paper.

IV. Virtual MIMO Construction

After the text edit has been completed, the paper is ready for the template. Duplicate the template file by using the Save As command, and use the naming convention prescribed by your conference for the name of your paper. In this newly created file, highlight all of the contents and import your prepared text file. You are now ready to style your paper; use the scroll down window on the left of the MS Word Formatting toolbar. In order to form a VMIMO multi-user, resources of two users are brought together. As described above, in order to achieve a low spatial correlation, two spaced antennas in the MS have been chosen and four spaced antennas elements in BS have been selected. Therefore, the resources of two users (U1 and U2) are brought together to form 4x4 VMIMO multi-user system with the BS. For users U1 and U2, the two spaced antennas correspond to the antennas 1 and 3 or the antennas 2 and 4. In our calculation, we consider the two spaced antennas 2 and 4 for each user that correspond to the dashed column matrix 2 and 4 of the user channel matrices as shown in Fig. 3. Then the two dashed column matrix of the two users channel matrices are brought together to set up a VMIMO multi-user channel matrices. The properties of the user_1 (U1) and user_2 (U2) will be analyzed and compared to those properties of VMIMO multi-user system formed by U1 and U2.

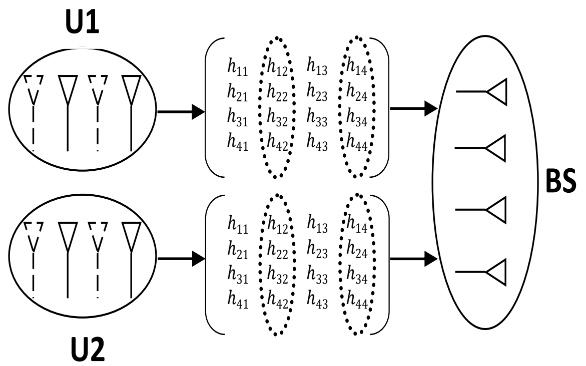

Fig. 3. Construction of 4 x 4 virtual MIMO system from standard users.

V. Joint Transmitter and Receiver Design with CSI

Joint transmitter and receiver design with CSI is referred to us as transmit and receive beamforming. However, beamforming can be defined as a technique to match the transmission and reception of signals to the channel through which they propagate.

In a particular beamforming design, a pre-or post-processing is performed at the antenna array so that the post-processing SNR corresponding to the link of interest is maximized.

A. *Multiple Transmit and Receive Beams*

An array of N antennas can form up to N different beans matched to Ndifferent communication links. Each beam can carry one stream of data. A multi-beam communication is better performed with an antenna array which is composed with antennas that are sufficiently apart communicating with devices that are spatially distinguishable. In such multi-beam communication, an antenna array can lead beams towards different directions. Different beams can be formed and pointed the direction of multiple users. When the users are sufficiently spatially separated, they can receive or send data without any interference between beams. Therefore, this configuration is assumed to be a line-of-sight communication.

For a MIMO link communication, one could believe that only a single beam can be successfully transmitted or received because the multiple antennas at a receiver are co-located and are not spatially distinguishable in most of the cases from a transmitter. Therefore, in order to successfully transmit or receive multiple beams, the scattering environment must be rich enough (presence of multiple path) or the antennas must be sufficiently separated or have a distinct pattern. Under this assumptions, the appropriate transmit and receive beamforming can extract distinct spatial paths by matching transmit and receive beams.

In this section, we will introduce different forms of single beam communications, such as transmit beamforming (MISO system) and receive beamforming (SIMO); and finally, we will give the description of multiple beam communications where beams are formed at the transmitter and receiver.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 12 Issue 01, January-2023

B. *Transmit beamforming (MISO system)*

In MISO system as illustrated in Figure 4., the transmit antenna is composed with N_t antennas and receiver is composed with one antenna. We denote $\tilde{x}$ a stream of data sent from transmitter to the receiver. A processed $\tilde{x}$ version will be transmitted from each transmit antenna. That is to say, before transmitting a stream of data $\tilde{x}$ to the receiver, its phase and amplitude are modified to match the channel. To do so, the stream of data sent from antenna i is weighted by a complex valued weight w_i^*. That is to say, the processed version $w_i^* \tilde{x}$ is sent from antenna i.

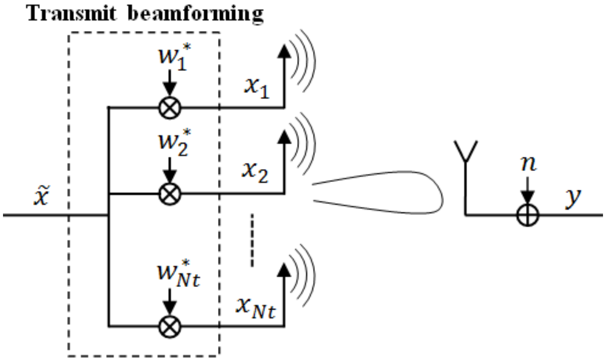

Figure. 4. MISO system model with transmit beamforming.

The weights must be selected in order to maximize the post-processing SNR at the receiver. As we can see in Figure 4, the processed signal $w_i^* \tilde{x}$ is sent from antenna i to the receiver. However, all the processed signals received by the receiver are added up constructively. Hence, we can describe the receiver in the form as:

$$y = \left(\sum_{i=1}^{N_t} h_i w_i^* \right) \tilde{x} + n \tag{2}$$

The signal is seen by the receiver like it has been transmitted from the channel $\sum_{i=1}^{N_t} h_i w_i^*$. However, we can rewrite the equivalent channel of the system as the scalar product: $\mathbf{w}^{\mathrm{H}}\mathbf{h}$ where $\mathbf{w}$ is given by: $\mathbf{w} = \left[w_1^* w_2^* \;\; \dots \;\; w_{N_t}^* \right]^{\mathrm{T}}$ is $N_t \times 1$ row vector and $\mathbf{h}$ is given by: $\mathbf{h} = \left[h_1 h_2 \;\; \dots \;\; h_{N_t} \right]^{\mathrm{T}}$ is a column vector. Therefore, we can rewrite the received processed signal as:

$$y = \mathbf{w}^{\mathrm{H}}\mathbf{h}\,\tilde{x} + n \tag{3}$$

Normally the transmit power is $\|w\|^2 E|\tilde{x}|^2$ and will be set to the maximum allowed transmit power $\bar{P}$.That is to say, we assume the system with no losses, therefore $\|w\|^2$is set equal to one, i.e.$\|w\|^2 = 1$, and $E|\tilde{x}|^2 = \bar{P}$. However, the power in the signal part of above equation is given as: $\bar{P}\left|\mathbf{w}^{\mathrm{H}}\mathbf{h}\right|^2$ and the noise power is given as: σ_n^2. Hence, the post-processing SNR is given by:

$$\mathrm{SNR} = \frac{\bar{P}\left|\mathbf{w}^{\mathrm{H}}\mathbf{h}\right|^2}{\sigma_n^2} \tag{4}$$

This post-processing SNR is maximized when the amplitude of the inner product $\left|\mathbf{w}^{\mathrm{H}}\mathbf{h}\right|^2$ is set to its maximum value. The scalar product is maximized when $\mathbf{w}$ and $\mathbf{h}$ is aligned. The maximum MISO transmit filter is transmit matched filtering. However, transmit matched filter (TMF) for MISO channel $\mathbf{h}$is $\mathbf{w}_{\mathrm{TMF}} = \mathbf{h}^*/\|\mathbf{h}\|$ [2, 3]. The TMF maximizes the post-processing SNR. The corresponding signal at receiver with TMF applied at transmitter is $y_{\mathrm{TMF}} = \|\mathbf{h}\|\tilde{x} + n$. Hence, the post-processing SNR can be rewrite as:

$$\mathrm{SNR} = \frac{\bar{P}\|\mathbf{h}\|^2}{\sigma_n^2} \tag{5}$$

Transmit matched filter transforms a MISO system into a SISO system by doing only a linear operations at the transmitter. This transformation of MISO system to SISO system does not results in any loss of information. TMF is a structure achieving capacity of a MISO system when CSIT and CSIR are known.

C. *Receive Beamforming (SIMO system)*

In SIMO system as illustrated in Figure 5., the transmit antenna is composed with one antenna and receiver is composed with N_r antennas. We denote x a stream of data sent from transmitter to the receiver. A multi-copy of the signal x is sent from a single transmitter and received by a multiple receive antennas. In order the received signal can added up constructively, the phase and amplitude of the received signal must be aligned. Therefore, one copy of stream of data x received by the receive antenna j is weighted by a complex scalar weight w_j^*. So all copies of stream of data x received by multiple receive antennas are weighted and added up. However, the corresponding receive signal is given by:

$$\tilde{y} = \left(\sum_{j=1}^{N_r} w_j^* h_j \right) x + \sum_{j=1}^{N_r} w_j^* n_j \tag{6}$$

The MF is the receiver maximizing the post-processing SNR[2].

The new system that is performed by applying the spatial matched filtering at the receiver, is equivalent to SISO system with channel equal to $\sum_{j=1}^{N_r} w_j^* h_j$. We will rewrite this equivalent as the inner product: $\mathbf{w}^{\mathrm{H}}\mathbf{h}$ where $\mathbf{w} = \left[w_1^* w_2^* \;\; \dots \;\; w_{N_r}^* \right]^{\mathrm{T}}$ is a row vector and $\mathbf{h} = \left[h_1 h_2 \;\; \dots \;\; h_{N_t} \right]^{\mathrm{T}}$ is a column vector. The noise part is $\mathbf{w}^{\mathrm{H}}\mathbf{n}$where$\mathbf{n} = \left[n_1 n_2 \;\; \dots \;\; n_{N_t} \right]^{\mathrm{T}}$.Therefore, we can rewrite the processed receive signal as:

$$\tilde{y} = \mathbf{w}^{\mathrm{H}}\mathbf{h}x + \mathbf{w}^{\mathrm{H}}\mathbf{n} \tag{7}$$

The signal power in above equation is $P_x\left|\mathbf{w}^{\mathrm{H}}\mathbf{h}\right|^2$, while the noise power is $\sigma_n^2\|\mathbf{w}\|^2$. The post-processing SNR is defined as:

$$\mathrm{SNR} = \frac{P_x\left|\mathbf{w}^{\mathrm{H}}\mathbf{h}\right|^2}{\sigma_n^2\|\mathbf{w}\|^2} \tag{8}$$

The post-processing SNR is optimal when the inner product $\mathbf{w}^{\mathrm{H}}\mathbf{h}$ is maximized. The amplitude of the inner product $\mathbf{w}^{\mathrm{H}}\mathbf{h}$ (with $\|\mathbf{w}\|^2 = 1$) is maximized when $\mathbf{h}$ and $\mathbf{w}$ are aligned. Therefore, the receiver after matched filter is $\mathbf{w}^{\mathrm{H}} = \mathbf{h}^{\mathrm{H}}/\|\mathbf{h}\|$. Hence, the post-processing SNR will be defined as:

$$\mathrm{SNR} = \frac{P_x\|\mathbf{h}\|^2}{\sigma_n^2} \tag{9}$$

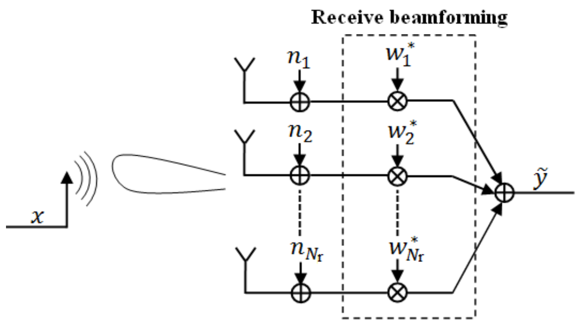

Figure. 5. SIMO system model with receive beamforming.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 12 Issue 01, January-2023

D. *Maximal Eigenmode Transmission*

The single beamforming design is shown in Figure 6., where both ends of communication link carry a multiple antennas and know the MIMO channel matrix. The maximal eigenmode beamforming is referred to us as a single beam MIMO where the system model is like a single beam is transmitted from the transmitter and single beam is received by the receiver [4, 5]. We denote $N_t \times N_r$ MIMO channel matrix$\mathbf{H}$, the $N_t \times 1$ transmit weight vector as $\mathbf{w}_{\text{tx}}$, and the $N_r \times 1$ receive weight vector as $\mathbf{w}_{\text{rx}}$. The stream of data $\tilde{x}$ is the transmitted signal, $\mathbf{x} = [x_1 x_2 \ \ldots \ x_{N_t}]^{\text{T}}$ is the input vectorial containing the signals sent from each transmit antenna and $\mathbf{y} = [y_1 y_2 \ \ldots \ y_{N_r}]^{\text{T}}$ is the vectorial output containing the signals received at each antenna. The maximum transmit power is set to $\bar{P}$. Hence all quantities of interest can be defined as:

The $N_t \times 1$ transmit signal is defined as: $\mathbf{x} = \mathbf{w}_{\text{tx}}\tilde{x}$ where $\| \mathbf{w}_{\text{tx}} \|^2 = 1$ and $E|\tilde{x}|^2 = \bar{P}$. The $N_r \times 1$ receive signal is defined as: $\mathbf{y} = \mathbf{H}\mathbf{w}_{\text{tx}}\tilde{x} + \mathbf{n}$. After receive beamforming the output of the receiver is given as: $\tilde{y} = \mathbf{w}_{\text{rx}}^{\text{T}}\mathbf{H}\mathbf{w}_{\text{tx}}\tilde{x} + \mathbf{w}_{\text{rx}}^{\text{T}}\mathbf{n}$ where$\| \mathbf{w}_{\text{rx}} \|^2 = 1$. Hence after beamforming the power of the signal part is $\bar{P}|\mathbf{w}_{\text{rx}}^{\text{T}}\mathbf{H}\mathbf{w}_{\text{tx}}|^2$ and power of the noise is $\sigma_n^2 \| \mathbf{w}_{\text{rx}} \|^2 = \sigma_n^2$. However, the post-processing SNR after beamforming is defined as:

$$\text{SNR} = \frac{\bar{P}|\mathbf{w}_{\text{rx}}^{\text{T}}\mathbf{H}\mathbf{w}_{\text{tx}}|^2}{\sigma_n^2} \quad (10)$$

In order to maximize this post-processing SNR after beamforming in equation (5.58), it is like as maximizing the signal power $\bar{P}|\mathbf{w}_{\text{rx}}^{\text{T}}\mathbf{H}\mathbf{w}_{\text{tx}}|^2$. The solution of this maximization is based on singular value decomposition of the channel matrix $\mathbf{H}$. A detail literature about singular value decomposition of channel matrix can be found in [2].

$$\mathbf{H} = \mathbf{U}\mathbf{\Lambda}\mathbf{V}^{\text{H}} = \sum_{k=1}^{r_{\text{H}}} \lambda_k \mathbf{u}_k \mathbf{v}_k^{\text{H}} \quad (11)$$

where $\mathbf{u}_k$and$\mathbf{v}_k$are the kth columns of $\mathbf{U}$ and $\mathbf{V}$ respectively. The term $\lambda_k$is the kth singular value. Therefore, we denote $\lambda_{\text{max}}$the maximum singular value of $\mathbf{H}$, $\mathbf{u}_{\text{max}}$ and $\mathbf{v}_{\text{max}}$the corresponding left and right singular vectors. However, we rewrite the $|\mathbf{w}_{\text{rx}}^{\text{T}}\mathbf{H}\mathbf{w}_{\text{tx}}|^2$ as: $|\mathbf{w}_{\text{rx}}^{\text{T}}\mathbf{U}\mathbf{\Lambda}\mathbf{V}^{\text{H}}\mathbf{w}_{\text{tx}}|^2$. It can be again decompose as:

$$| \mathbf{w}_{\text{rx}}\mathbf{H}\mathbf{w}_{\text{tx}} |^2 = |\left(\mathbf{w}_{\text{rx}}\mathbf{U}\mathbf{\Lambda}^{1/2}\right)\left(\mathbf{\Lambda}^{\text{H}/2}\mathbf{V}^{\text{H}}\mathbf{w}_{\text{tx}}\right)|^2 \quad (12)$$

The beamforming vectors $\mathbf{w}_{\text{tx}}$ and $\mathbf{w}_{\text{rx}}$ should extract a spatial path with the highest possible energy. This is possible by matching $\mathbf{w}_{\text{tx}}$ to the right singular value of $\mathbf{H}$ with a highest singular value and by matching $\mathbf{w}_{\text{rx}}$ to the corresponding left singular vector. Therefore, the transmit beamforming vector $\mathbf{w}_{\text{tx}}$ is $\mathbf{V}_{\text{max}}$. Hence, the product $\mathbf{\Lambda}^{\text{H}/2}\mathbf{V}^{\text{H}}\mathbf{w}_{\text{tx}}$ is equal to $\lambda_{\text{max}}^{1/2}$. The receive beamforming vector $\mathbf{w}_{\text{rx}}$ is $\mathbf{U}_{\text{max}}^*$. Hence, the product $\mathbf{w}_{\text{rx}}\mathbf{U}\mathbf{\Lambda}^{1/2}$ is equal $\lambda_{\text{max}}^{1/2}$.

As a resume, both transmitter and receiver form a single beam in maximal eigenmode transmission. The transmit beamforming vector is equivalent to $\mathbf{V}_{\text{max}}$ and receive beamforming vector is equivalent to $\mathbf{U}_{\text{max}}^*$. Hence, the signal at the receiver after beamforming is defined as:

$$\tilde{y} = \lambda_{\text{max}}\tilde{x} + \tilde{n} \quad (13)$$

$\tilde{n} = \mathbf{V}_{\text{max}}^{\text{H}}\mathbf{n} \sim CN(0, \sigma_n^2)$. With this transmit and receive beamforming the system will become equivalent to a SISO system. Hence, the post-processing SNR can be rewrite as:

$$\text{SNR} = \frac{\bar{P}\lambda_{\text{max}}{}^2}{\sigma_n^2} \quad (14)$$

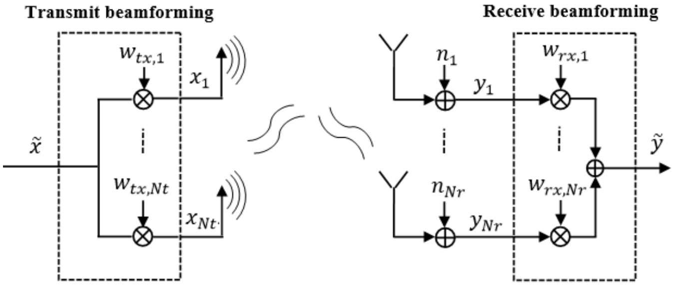

Figure. 6. Single beam MIMO system with transmit and receive beamforming.

E. *Eigenmode Transmission*

In a maximal eigenmode transmission we have imposed a single beam communication. However, when the channel possesses more than one non-zero singular value, it is possible to form multiple beams and send independent data stream using those beams. Instead of communication only over the channel with the maximal eigenvalue, we communicate over all the eigenchannels: such a transmission is called eigenmode transmission [6, 7]. We can form as many beams as nonzero singular values as illustrated in Figure 7., example of 2×2 MIMO system. This approach focuses on maximizing the total system throughput, while maximal eigenmode transmission focuses on a single stream communication and on maximizing the post-processing SNR and hence the throughput of this single stream.

Let us first examine the case of two transmit and two receive antennas. Let us recall the notations linked to the singular value decomposition of $\mathbf{H}$.

$$\mathbf{H} = \mathbf{U}\mathbf{\Lambda}\mathbf{V}^{\text{H}} \quad (15)$$

$\mathbf{\Lambda} = \text{diag}(\lambda_1, \lambda_2)$ is a diagonal matrix with diagonal elements equal λ_1 to and λ_2, and $\lambda_1 \geq \lambda_2$. The terms $\mathbf{U} = [\mathbf{u}_1 \mathbf{u}_2]$ and $\mathbf{V} = [\mathbf{v}_1 \mathbf{v}_2]$ are unitary matrices. $\mathbf{u}_1$ and $\mathbf{u}_2$are the first and second column of $\mathbf{U}$ and the left singular vectors of $\mathbf{H}$. $\mathbf{v}_1$ and $\mathbf{v}_2$ are the first and second column of $\mathbf{V}$ and the right singular vectors of $\mathbf{H}$.

$$\mathbf{u}_i = \begin{bmatrix} u_{2i} \\ u_{2i} \end{bmatrix} \text{ and } \mathbf{v}_i = \begin{bmatrix} v_{2i} \\ v_{2i} \end{bmatrix} \quad (16)$$

The SVD of $\mathbf{H}$ can alternatively be written as:

$$\mathbf{H} = \lambda_1 \mathbf{u}_1 \mathbf{v}_1^{\text{H}} + \lambda_2 \mathbf{u}_2 \mathbf{v}_2^{\text{H}} \quad (17)$$

At the transmitter if we want to reach optimal performance, the power should be distributed optimally among the beams. This is a significant difference with the single beamforming MIMO case of Section 5.3.5. Power allocation becomes part of the optimization problem. We denote as P_i the power assigned to be i. The maximum overall transmit power is $\bar{P}$. Hence, the transmit power is $P_1 + P_2 \leq \bar{P}$.

The first transmit beamforming vector is $\mathbf{v}_1$ and is used to send symbol $\tilde{x}_1 (E|\tilde{x}_1|^2 = P_1)$. The second transmit beamforming vector is $\mathbf{v}_2$and is used to send symbol $\tilde{x}_2 (E|\tilde{x}_2|^2 = P_2)$. The transmit vector corresponding to the first beam is $\mathbf{v}_1\tilde{x}_1$ while the transmitted vector correspond to the second beam is $\mathbf{v}_2\tilde{x}_2$. The beams are added up and the $N_t \times 1$ transmitted signal is:

$$\mathbf{x} = \mathbf{v}_1\tilde{x}_1 + \mathbf{v}_2\tilde{x}_2 \quad (19)$$

At receiver by using equation (5.65), the received signal is:

$$\begin{aligned} \mathbf{y} &= \mathbf{H}(\mathbf{v}_1\tilde{x}_1 + \mathbf{v}_2\tilde{x}_2) + \mathbf{n} \\ &= \lambda_1 \mathbf{v}_1 \tilde{x}_1 + \lambda_2 \mathbf{v}_2 \tilde{x}_2 + \mathbf{n} \end{aligned} \quad (20)$$

At the receiver, the task is to separate both streams to recover $\tilde{x}_1$ and $\tilde{x}_2$. This task is made easy because of the orthogonality properties of the received streams. From equation (5.67), the 2×2 equivalent channel corresponding to the transmission of $\tilde{x}_1$ and $\tilde{x}_2$ is:

$$[\lambda_1 \mathbf{u}_1 \quad \lambda_2 \mathbf{u}_2] \qquad (21)$$

This matrix is orthogonal because its columns are orthogonal. The optimal receiver is the spatial matched filter. However, to recover the stream 1, the optimal receiver is the spatial filter matched to $\mathbf{u}_1$, that is, $\mathbf{u}_1^{\mathrm{H}}$, which also eliminates the contribution of the second beam. The output of the receiver is $\tilde{y}_1 = \lambda_1 \tilde{x}_1 + \mathbf{u}_1^{\mathrm{H}}\mathbf{n}$. Like recovering the stream 1, to recover the stream 2, the optimal receiver is the spatial filter matched to $\mathbf{u}_2$, that is $\mathbf{u}_2^{\mathrm{H}}$. Hence, output is $\tilde{y}_2 = \lambda_2 \tilde{x}_2 + \mathbf{u}_2^{\mathrm{H}}\mathbf{n}$.

However, the system that includes transmit and receive beamforming filters becomes:

$$\tilde{y}_1 = \lambda_1 \tilde{x}_1 + \tilde{n}_1$$
$$\tilde{y}_2 = \lambda_1 \tilde{x}_2 + \tilde{n}_2 \qquad (22)$$

where $\tilde{n}_1 = \mathbf{u}_1^{\mathrm{H}}\mathbf{n}$ and $\tilde{n}_2 = \mathbf{u}_2^{\mathrm{H}}\mathbf{n}$. $\tilde{n}_1$ and $\tilde{n}_2$ are independent and $\tilde{n}_j \sim CN(0,\ \sigma_n^2 \mathbf{I})$. Hence, we have created two independent spatial channels or parallel channels with respective SNRs:

$$\mathrm{SNR}(1) = \frac{P_1 \lambda_1^2}{\sigma_1^2} \quad \text{and} \quad \mathrm{SNR}(2) = \frac{P_2 \lambda_2^2}{\sigma_2^2} \qquad (23)$$

We have to look for the beam with a strong SNR. Therefore, all the power is allocated to the beam with strong SNR.

Eigenmode transmission involves many parallel channels and hence more than one SNR. In this case of two different SNRs, it is not possible to maximize at the same time the two SNRs: when one SNR is increased, the other SNR is decreased. An optimization design relies on the achievable rate, where the optimal power allocation is the one maximizing the system capacity.

Since the channels are independent each other's the achievable rate of the whole system is the sum of the capacity of the parallel channels:

$$\mathcal{R}_{\max} = \log_2[1 + \mathrm{SNR}(1)] + \log_2[1 + \mathrm{SNR}(2)]$$

The total power $\bar{P}$ is: $\bar{P} = P_1 + P_2 \Rightarrow P_2 = \bar{P} - P_1$, when replacing P_2 by $\bar{P} - P_1$ we obtain:

$$\mathcal{R}_{\max} = \log_2\left[1 + \frac{P_1 \lambda_1^2}{\sigma_1^2}\right] + \log_2\left[1 + (\bar{P} - P_1)\frac{\lambda_2^2}{\sigma_2^2}\right] \qquad (24)$$

This expression can be optimized with respect to P_1. The solution is as follows:

$$P_i^0 = \left(\frac{1}{\gamma_0} - \frac{1}{\gamma_i}\right)^+ \qquad (25)$$

where $x^+ = x$ if $x \geq 0$ and $x^+ = 0$if $x < 0$. γ_0 is a value derived from the constraint $P_1^0 + P_2^0 = \bar{P}$. Computation of transmit power is done as follows:

- First we compute the constant γ_0 assuming that both channels are allocated power, that is, P_1^0 and P_2^0 are positive. We find $1/\gamma_0 = (\bar{P} + 1/\gamma_1 + 1/\gamma_2)/2$.
- Next, we need to check that P_1^0 and P_2^0 thanks to this value $1/\gamma_0$ are positive. We assume that $\lambda_1 \geq \lambda_2$, hence $1/\gamma_2 \geq 1/\gamma_1$ and $P_2^0 \leq P_1^0$. So, we need first to check if P_2^0 is positive.

If $P_2^0 = 1/\gamma_0 + 1/\gamma_2 \geq 0$, then both eigenchannels are allocated. The power is as in equation (5.73). If $P_2^0 = 1/\gamma_0 + 1/\gamma_2 < 0$, then $P_2^0 = 0$ and $P_1^0 = \bar{P}$. All the power is allocated to the first beam. In such a case, it is better to allocate all the power to the beam with stronger SNR. This process is called WF and is described in the reference [8, 9].

From the previous 2×2 MIMO system, the generalized $N_t \times N_r$ MIMO system can obtained as described below. Eigenmode transmission with WF is a multiple transmit and receive beam techniques where the beams are matched to the underlying structure of the channel given by the SVD of the channel matrix $\mathbf{H} = \boldsymbol{U\Lambda V}^{\mathrm{H}}$:

- r_{H} transmit beams: $\mathbf{v}_1, \ldots, \mathbf{v}_{r_{\mathrm{H}}}$.
- r_{H} receive beams: $\mathbf{u}_1^*, \ldots, \mathbf{u}_{r_{\mathrm{H}}}^*$.
- The transmit power is allocated across eigenmode as:

$$P_i^0 = \left(\frac{1}{\gamma_0} - \frac{1}{\gamma_i}\right)^+ \qquad (26)$$

γ_0 is the cut-off value and is determined using the power constraint:

$$\sum_{i=1}^{r_{\mathrm{H}}} P_i^0 = \sum_{i=1}^{r_{\mathrm{H}}} \left(\left(\frac{1}{\gamma_0} - \frac{1}{\gamma_i}\right)^+\right) = \bar{P} \qquad (27)$$

Eigenmode transmission with WF is an optimal structure for MIMO systems when the channel is time-invariant and is known (along with the noise variance) at the transmitter.

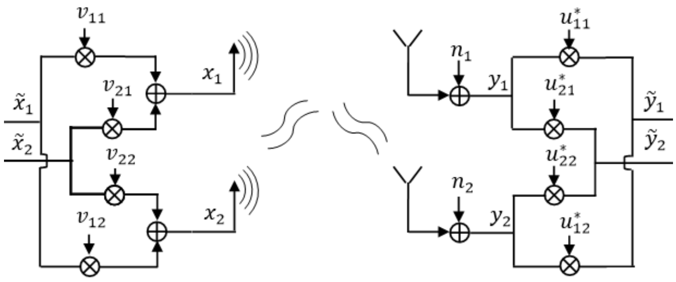

Figure. 7. Multiple beams Eigenmode transmission.

The Figure 8. below is plotted using measurement data to show the performance of single beam transmission known as Maximal eigenmode transmission, and multiple beam transmission with WF and equally distributed transmit power. The maximum transmission rate is seen with multiple beam transmission with WF at law SNR. At high SNR multiple beam transmission with water-filing will become equivalent to multiple beam transmission with equally distributed transmit power.

The Figure 8. shows also a comparison between V-MIMO and SU-MIMO. The maximum achievable rate is seen with V-MIMO. The idea behind is to validate the performance gains with V-MIMO over SU-MIMO using practical transmit and receive design. Only two measurement datasets (two users) have been used. The resources of that two users are bought together to form a V-MIMO system. The comparison is made between V-MIMO system and one of the selected users.

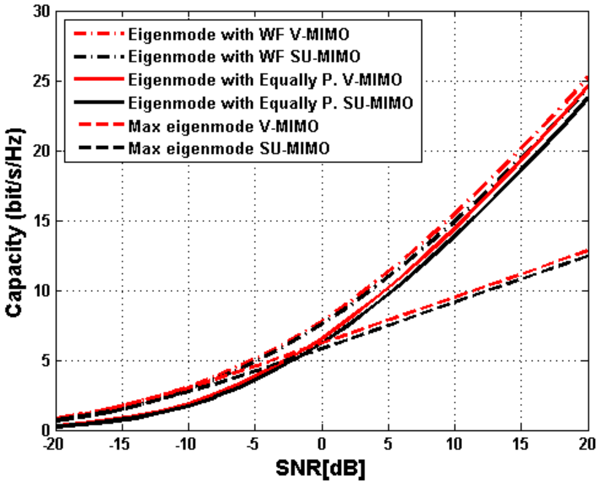

Figure. 8. Capacity of eigenmode transmission (single and multiple beams) with measurement data.

VI. CONCLUSION

In this paper, the MIMO joint transmitter and receiver design with CSI were investigated using measurement data. Those schemes have been also investigated in order to make a comparison between the V-MIMO and the conventional MIMO systems.

In joint transmitter and receiver design with CSI, the maximal eigenmode (single beam) and eigenmode (multiple beams) transmission were investigated. The eigenmode transmission achieves capacity than maximal eigenmode. In eigenmode transmission, we distinguish two modes of transmission, such as eigenmode transmission with WF and eigenmode transmission with equal distributed power. The eigenmode transmission with WF achieves capacity compared to eigenmode transmission with equal distributed power at low SNR, but at high SNR the two eigenmode transmissions will become equivalent.

As aforementioned, MIMO joint transmitter and receiver design with CSI have been investigated to show the performance of V-MIMO system. It is found that with eigenmode transmission with WF, the maximum achievable rate is seen with the V-MIMO system compared to the conventional MIMO system [10].

ACKNOWLEDGMENT

This work was supported by the Ministry of Higher Education and Scientific Research of Mali.

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