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Measurement Based Mutual Information Analysis of Beam Steering in the 60 GHz Band

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Abstract— This paper presents the performance evaluation of a system using beam steering technique at RX, based on 60 GHz MIMO measurement data. The mutual information of this system is compared to the one of a traditional MIMO system, considering ideal and realistic phase shifters. It is found that with lossless phase shifters and power combiner, the mean mutual information obtained by selecting the best beam out of 5 is higher than the one of 2x2, 3x3 and 4x4 MIMO at low SNR. When considering realistic components, the mean mutual information obtained by selecting the best beam out of 5 is only higher than the one of 2x2 MIMO at low SNR. In both cases (with lossless and realistic phase shifters) MIMO outperforms beam steering at high SNR.

I. INTRODUCTION

The need for higher data transmission rates is growing all the time. One solution for responding to this demand is to use the unlicensed frequency band around 60 GHz for short range mobile communications [1]-[3]. This band offers huge bandwidth and, due to the short wavelength, several antenna elements can be integrated into a small volume, which allows the use of multi-antenna techniques. Several techniques with different complexity and performance have been studied such as Multiple-Input Multiple-Output (MIMO) [4], [5] or beam steering [6] to increase the data rate. Beam steering techniques require lower computational burden than MIMO [7], but the transmission rate can be lower. At 60 GHz, the performance of MIMO technique has been verified experimentally [8]. Nevertheless, the performance of beam steering in real environment (based on measurements) has not been compared to that of traditional MIMO.

II. MEASUREMENT CAMPAIGN

The measurement equipment and measurement environments have been presented in [8]. The channel sounder utilizes virtual 3-D antenna arrays to perform MIMO channel measurements. This means that there is only one antenna at Rx and Tx and the antennas are moved with accurate scanners. The use of virtual antenna arrays enables free choice of the shape of the antenna array configurations. In the channel measurements 25 square antenna arrays were used at Tx and Rx with element spacing 1λ . As can be seen from Fig. 1, there were 24 Tx positions and 1 Rx position in the radio channel measurements.

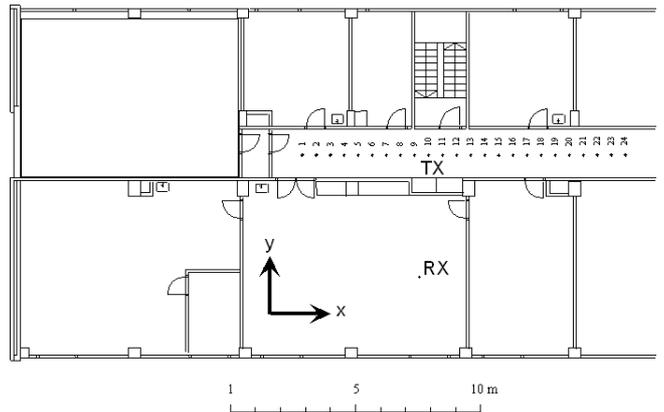


Fig. 1 Measurement environment.

III. RESULTS

A. Mutual Information Calculation

The channel mutual information for different configurations is calculated using the measurement data reported in [8]. From the 25 elements arrays, smaller sub-arrays (5x1 linear arrays) are chosen for the channel capacity calculation. Beam steering is performed only at Rx, with 5x1 linear arrays. The antenna array at Tx consists also of 5 antenna elements. Hence, there are $(5+5)^2 = 100$ antenna array combinations for each measurement point. In Fig. 2 the radiation patterns of the 5x1 linear antenna arrays with the different beam directions are plotted. The beams are directed by adding phase shift to the signals received by antenna elements and by summing these five signals together. It can be seen from Fig. 2 that 5 different beams are needed to cover the whole azimuth range ($0^\circ - 360^\circ$) so that the variation of the amplitude is less than 4 dB. The wide back lobes are due to the antenna element spacing of 1λ .

The channel mutual information of beam steering and MIMO techniques is calculated based on [4]:

$$C = \log_2 \left[\det \left(\mathbf{I} + \frac{\rho}{n_t} \bar{\mathbf{R}}_{norm} \right) \right] \text{ bit/s/Hz} \quad (1)$$

The normalized channel correlation matrix is calculated according to

$$\bar{R}_{norm} = \frac{\bar{H}^H \bar{H}}{\frac{1}{n_t n_r} \sum_{t=1}^{n_t} \sum_{r=1}^{n_r} \bar{H}_{r,t}^* \bar{H}_{r,t}} \quad (2)$$

where $(\cdot)^H$ is complex conjugate transpose, $(\cdot)^*$ is complex conjugate. n_t and n_r are the numbers of transmitting and receiving antenna elements, respectively. \bar{H} is a narrowband complex channel matrix obtained from impulse responses by first removing noise and then using coherent summing in the delay domain. To calculate the capacity of beam steering configuration (1) and (2) are used with $n_t = 5$ and $n_r = 1$.

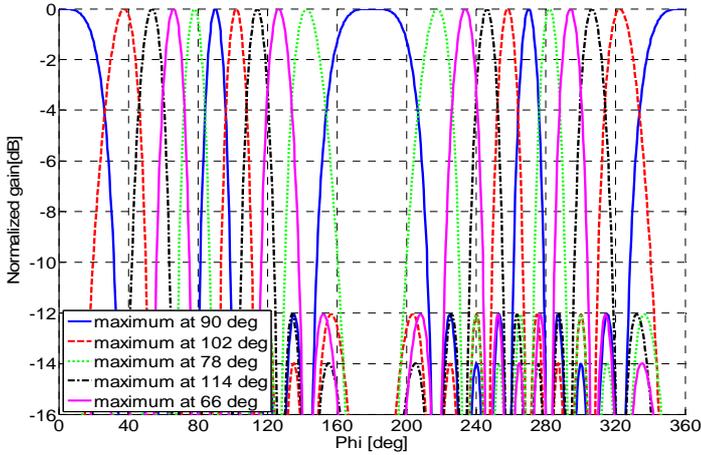


Fig. 2a. Normalized radiation patterns of the 5 element linear array with inter-elements spacing of 1λ .

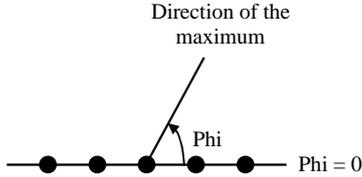


Fig. 2b. Definition of the maximum direction.

B. Theoretical Case

In this section, the phase shifters and the five-to-one power combiner that are needed to steer the beam are assumed to be lossless. Fig. 3 shows the channel mutual information obtained by selecting separately each beam. The mutual information obtained by selecting the best beam out of five is plotted in Fig. 4, together with the mutual information of traditional 5x5 MIMO, at SNR = 0, 10 and 20 dB. It is found that at almost all probability levels, beam steering leads to lower mutual information than 5x5 MIMO.

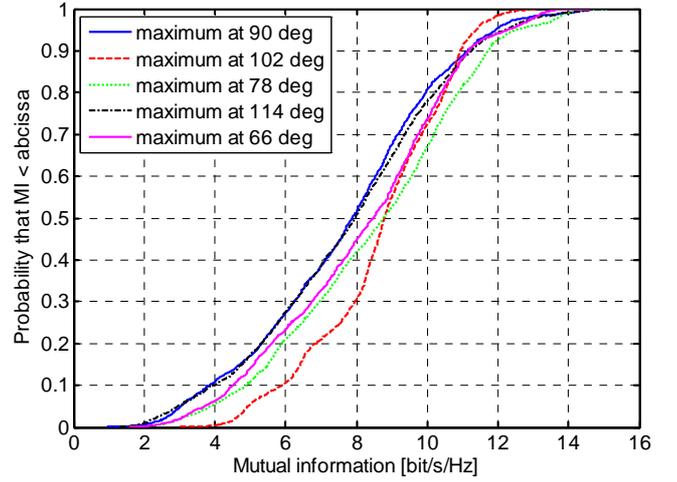


Fig. 3. Mutual information obtained using beam steering and 5 different steering angles (SNR = 20 dB)

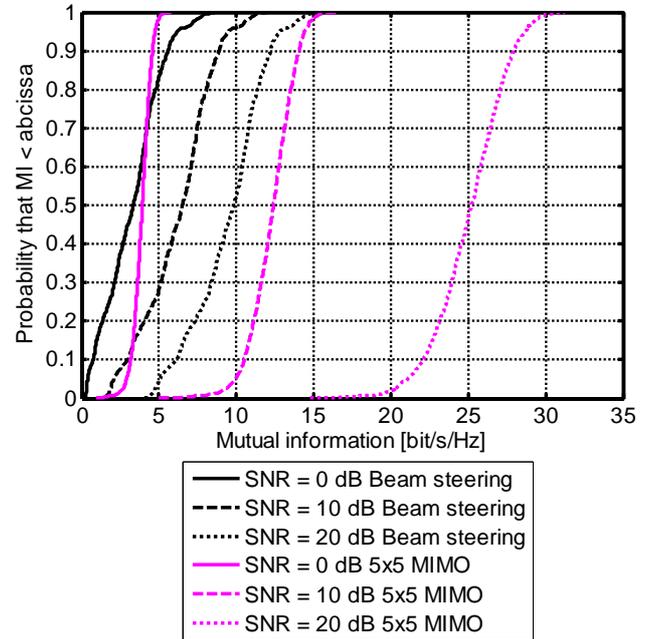


Fig. 4. Mutual information obtained by selecting the best beam out of five (lossless phase shifters and power combiner), together with the mutual information of traditional 5x5 MIMO, at SNR = 0, 10 and 20 dB.

Fig. 5 shows the mean mutual information obtained by selecting the best beam out of five, together with the mean mutual information of 2x2, 3x3, 4x4 and 5x5 MIMO, as a function of SNR. It is seen that beam steering outperforms 2x2, 3x3 and 4x4 MIMO, at SNR below 15 dB, 6 dB and 1 dB, respectively. Fig. 6 shows the mutual information at 10% probability level obtained by selecting the best beam out of five, together with the mutual information of 2x2, 3x3, 4x4 and 5x5 MIMO, as a function of SNR. It is seen that at 10% probability level all MIMO systems outperform beam steering.

C. Realistic Case

In this section, the losses of the RF phase shifters that are needed to steer the beam as well as the losses of the five-to-one power combiner are taken into account. Insertion losses of 3 dB were found for a distributed analog MEMS phase shifter [9] and 2 dB for the power combiner. The latter value was obtained by simulating a five-to-one power combiner on high resistivity silicon substrate at 60 GHz. Those values are chosen as representative in this work. Since the total loss depends on many parameters such as phase shifter topology, substrate properties, as well as the technology used to fabricate the whole circuit, the values given above are only estimates of realistic phase shifter.

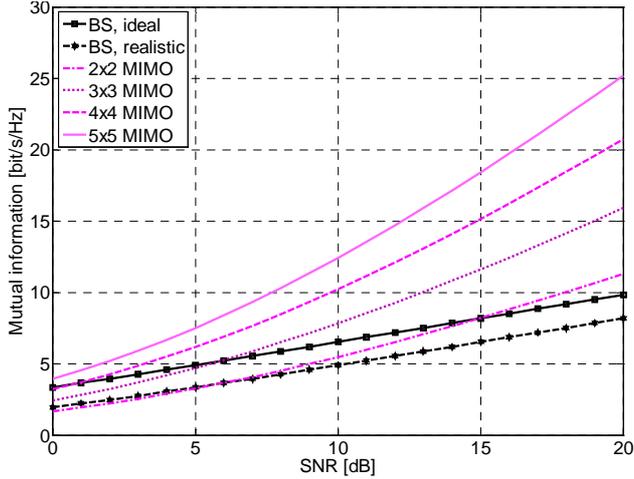


Fig. 5. Mean mutual information obtained by selecting the best beam out of five, together with the mean mutual information of 2x2, 3x3, 4x4 and 5x5 MIMO as a function of SNR.

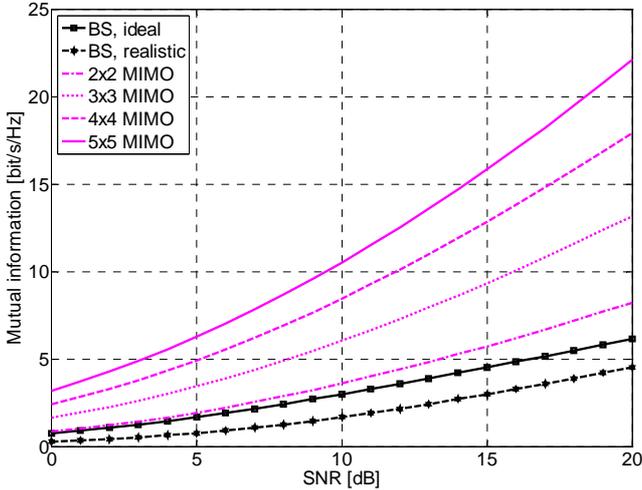


Fig. 6. Mutual information at 10% probability level obtained by selecting the best beam out of five, together with the mutual information of 2x2, 3x3, 4x4 and 5x5 MIMO as a function of SNR.

It can be seen from Fig. 5 that at 50% probability level beam steering outperforms 2x2 MIMO only at SNR below 6 dB. Due to the losses of the components, the mean mutual information is decreased by about 41% and 17% at SNR = 0 dB and 20 dB, respectively. From Fig. 6, it is seen that at 10% probability level MIMO outperforms beam steering with a larger gap than in the case with lossless components. Fig. 7. shows the mutual information obtained by selecting the best beam out of five, together with the mutual information of traditional 5x5 MIMO, at SNR = 0, 10 and 20 dB.

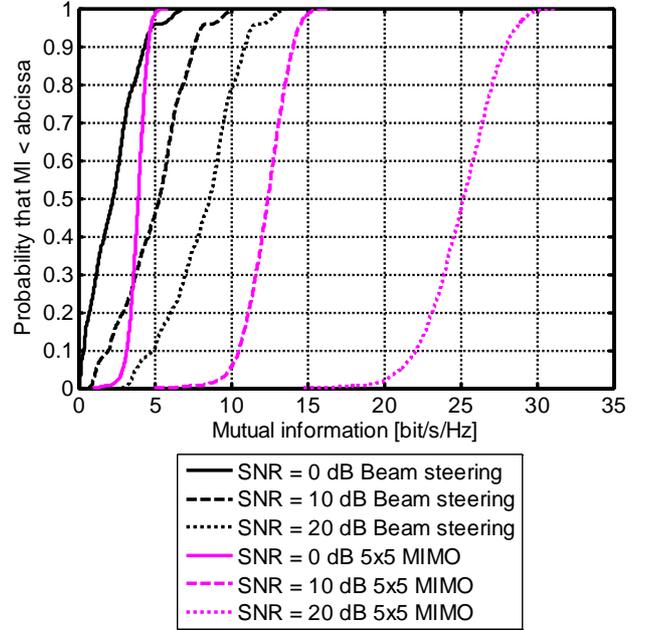


Fig. 7. Mutual information obtained by selecting the best beam out of five (phase shifters and power combiner with realistic losses), together with the mutual information of 5x5 MIMO, at SNR = 0, 10 and 20 dB.

IV. CONCLUSIONS

This paper presents the comparison, based on measurement data, between beam steering and traditional MIMO techniques, in term of mutual information. Beam steering technique is applied at RX, using 5 elements in line with inter elements spacing of one λ . Similar array geometry is used at TX so that the mutual information is calculated for 5x1 MISO system. Five different phase shifts are applied at RX in such a way that the full 360° azimuth range is covered with maximum variation of 4 dB. With lossless phase shifters and power combiner, the mean mutual information obtained by selecting the best beam out of 5 is higher than the one of 2x2, 3x3 and 4x4 MIMO at low SNR, but at 10 % probability level MIMO outperforms beam steering at all SNR. When considering realistic components, the mean mutual information obtained by selecting the best beam out of 5 is only higher than the one of 2x2 MIMO at low SNR.

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