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Measurement-based mutual information analysis of MIMO antenna selection in the 60 GHz band

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Abstract- **The mutual information (MI) of several MIMO antenna selection configurations has been studied based on 60 GHz MIMO channel measurement data. Several array shapes with different numbers of available antennas have been considered. The effect of the switching network (either lossless or with realistic losses) as well as the influence of the selection criterion (either maximum SNR or optimum capacity criterion) has been analyzed. It is found that in the best case (optimum capacity criterion and lossless switching network) antenna selection can increase the MI by up to 127 % as compared to traditional MIMO systems. Nevertheless, with more reasonable conditions (maximum SNR criterion, realistic switching network) the MI decreases drastically, with a maximum improvement of only 11% as compared to traditional MIMO systems.**

I. INTRODUCTION

To provide more than one Gbit/s data rates over short distances, the 60 GHz band has been considered [1]. This frequency band is of great interest because it offers at least 5 GHz licence-free bandwidth available worldwide. In addition, due to the short wavelength (about 5 mm) antenna arrays with a large number of elements can be built in small volume such as the corner of a laptop, a PDA (Personal Digital Assistant) or a mobile phone. Therefore, this band is one of the best candidates for future short range high data rate wireless communication systems such as high speed internet access, HDTV transmissions or wireless USB. Furthermore, in order to increase the spectral efficiency, multiple input multiple output (MIMO) systems have been studied extensively for many years because they can significantly enhance the data rate as compared to conventional single input single output (SISO) systems [2]. Nevertheless, MIMO systems have several drawbacks: increase of hardware complexity, cost and computational burden. Since antenna arrays can be manufactured at relatively low cost, a solution which consists of selecting only a restricted number of antennas among the whole antenna array has been studied [3]-[7], and is referred to as MIMO antenna selection or hybrid selection/MIMO (H-S/MIMO). This technique reduces the computational time as well as the number of RF chains - including low-noise amplifiers, up or down converters and analog-to-digital converters. By using MIMO antenna selection, significant efficiency improvement in term of mutual information (MI) unit per RF chain has been shown, as compared to traditional MIMO. However, most of the published research works use theoretical channel models for the MI calculations. No measurement-based MIMO antenna selection study at 60 GHz is found in the literature. Furthermore, as it was suggested in [3] and will be shown in this work, one of the most limiting factors of antenna selection are the losses in the switching network, but no thorough investigation on the effect of this is found in the literature. The results presented here give novel information about the MI of MIMO antenna selection in a real propagation environment at 60 GHz considering both ideal and realistic switching networks.

II. MIMO MEASUREMENTS

The propagation data are based on a measurement campaign performed at 61.3 GHz with a mm-wave MIMO channel sounder developed at Helsinki University of technology (TKK). The radiating elements were omnidirectional biconical antennas with 5 dBi gain and a half power beam width of 11º in elevation. The arrays, identical at TX and RX, consisted of 5 x 5 elements forming a square in the horizontal plane. Therefore, the total number of channels per snapshot was 25 x 25 = 625. The distance between two consecutive elements was one wavelength.

The measurement location is shown in Fig. 1. The RX was kept in a laboratory room with many measurement devices, computers and metal shelves while the TX was placed in 24 positions along a corridor with 50 cm steps. The total number of measured channel was 625 x 24 = 15000. All the measurements were with non line of sight (NLOS) condition, with antennas placed 1.5 m above the floor. A detailed description of the measurement setup and the measurement campaign can be found in [8].

III. SELECTION OF ANTENNAS IN SUB-ARRAYS

A. Antenna configuration

Since the number of available elements in antenna arrays of hand-held devices will be most likely less than 25, and in order to have more reliable statistical results, the best antennas were chosen in subsets of the original 25 element arrays. Several sub-array configurations were investigated: 4 consecutive elements in a line (row or column), 4 elements in a square, 5 consecutive elements in a line (row or column), and 9 elements in a square. For each sub-array configuration, the selections of two elements out of N and three elements out of N are studied, where N is the number of available elements in the sub-array (i.e. 4, 5 or 9). As an example, the selection of 3 elements out of 9 is shown in Fig. 2. The antenna selection is done only at one end of the link at a time, either at TX or RX. The number of elements at the other end of the link is the same as the one of selected elements, two or three. Therefore, the MI was calculated either for 2 x 2 or 3 x 3 MIMO systems. When the selection is done at TX, the channel state information (CSI) is assumed to be perfectly known at the transmitter. The total number of selected channels is between 270 and 800 for each of the 24 measurement points, depending on the configuration.

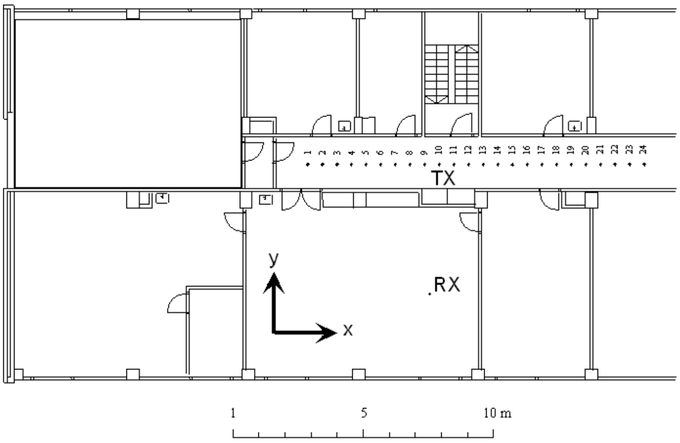

Fig. 1 Measurement location.

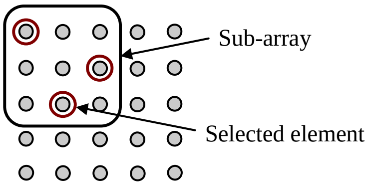

Fig. 2. Example of 3 selected antennas out of a sub array of 9 elements in square.

B. Selection criterion

To select the "best" antennas in an array, several criteria and algorithms have been studied [4], [5], [6] and [7].

In this work, the MI for all the configurations are analyzed using the signal to noise ratio (SNR) criterion (SNRC) and the optimum capacity criterion (OCC)[4], [6], [7]. The SNRC requires the lowest complexity scheme but leads to the maximum MI only at low SNR [6]. The OCC leads to the maximum MI but is computationally very expensive [4], [5], [6], [7].

The SNRC consists of selecting the antennas which lead to the highest SNR. The OCC consists of calculating the MI of all possible combinations within the sub-arrays and selects the antennas that maximize the MI.

The total number of channels to be analyzed is between 1,920 and 22,680, depending on the configuration, for each of the 24 measurement points. Since the MI of each channel has to be calculated for the OCC, it is unrealistic to expect that such criterion could be used with the processing power available today in hand-held devices, but it is an interesting criterion since it gives the upper bound for the MI.

C. Switching networks

As mentioned in [3], the switching network is a limiting factor in the antenna selection gain. This is especially important at 60 GHz since switches and transmission lines are lossier than at lower frequencies. For this reason, both ideal and realistic switching networks were considered when calculating the MI. For low loss switches, insertion losses of 1 dB was found for a single-pole double-throw (SP2T) in [9] and 1.6 dB was found for a single-pole triple-throw (SP3T) in [10]. Those values were chosen as representative values in this work. To take into account the losses due to the extra length of the transmission line (TL), an additional loss of 0.4 dB / wavelength was applied. This value was found by simulating a traditional 50 Ω coplanar waveguide (CPW) TL on high resistivity silicon substrate at 60 GHz. The number and type of the switches together with their total insertion loss, the estimated extra length of the TL and the total loss of switching networks are presented in Table 1 for the four sub-array configurations. Since the total loss depends on many parameters such as switching network topology, substrate properties, as well as the technology used to fabricate the switches and the whole network, the values given below are only estimates of realistic switching networks.

TABLE 1.
NUMBER, TYPE AND TOTAL INSERTION LOSS OF SWITCHES, ESTIMATED EXTRA LENGTH OF TL AND TOTAL LOSS OF SWITCHING NETWORKS

	Switches in series	Total loss due to switches (in dB)	Extra length of TL (in wavelengths)	Total loss of switching network (in dB)
4 in line	2 x SP2T	2	2	2.8
4 in square	2 x SP2T	2	2.5	3
5 in line	SP2T + SP3T	2.6	2.5	3.6
9 in square	2 x SP3T	3.2	3	4.4

IV. RESULTS

The MI of a MIMO system with N uncorrelated sources with equal power is given by

$$C = \log_2\left[\det\left(\mathrm{I}_M + \frac{\rho}{N}\mathrm{H}\mathrm{H}^*\right)\right] \quad \text{bit/s/Hz} \qquad (1)$$

where I_M is the identity matrix, H is the M x N channel matrix, (*) means transpose conjugate and ρ is the SNR at any RX antenna [2].

There are all together 16 options for each sub-array shape: either two or three selected antennas, either with ideal or realistic switching network, either with SNRC or OCC and either with antenna selection at TX or RX. The MI of all these options were calculated using (1). Due to the restricted length of this Letter, not all the 16 options can be discussed in details. Only the MI of the four most relevant cases will be presented and analyzed:

Case 1: 2 RX out of N with OCC and the ideal switching network, which represents the most favorable case (in term of MI).

Case 2: 3 RX out of N, with OCC and the ideal switching network. By comparing this case to *case 1*, the influence of the number of selected elements can be seen.

Case 3: 2 RX out of N available antennas with SNRC and the ideal switching network. The effect of the selection criterion will be analyzed by comparing this case to *case 1*.

Case 4: 2 RX out of N available, with the SNRC and the realistic switching network, which represents somewhat the worst case (in term of MI), but also the most realistic one, among 2 elements out of N cases. By comparing this case to *case 3*, the influence of the switching network will be discussed.

In addition, general comments about all the 16 options will be given in subsection IV.B.

A. Most relevant cases

Case 1

The MI obtained by selecting 2 RX out of *N* with OCC and the ideal switching network are compared to the MI of traditional 2x2 and 3x3 MIMO at SNR = 0, 10 and 20 dB in Fig. 3. The maximum MI increase at 10% probability, as compared to traditional 2x2 MIMO, is 127.8%, and is obtained with the 9 element sub-array, at SNR = 0 dB. The minimum MI increase at the same probability level is 29.5%, and is obtained with the 4 element in line sub-array at SNR = 20 dB. This case shows the highest MI increase among all 16 options. In addition, it can be noticed that at 10 % probability, at SNR = 0 and 10 dB, the selection of the 2 best antennas in the 9 element sub-array leads to higher MI than the traditional 3x3 MIMO.

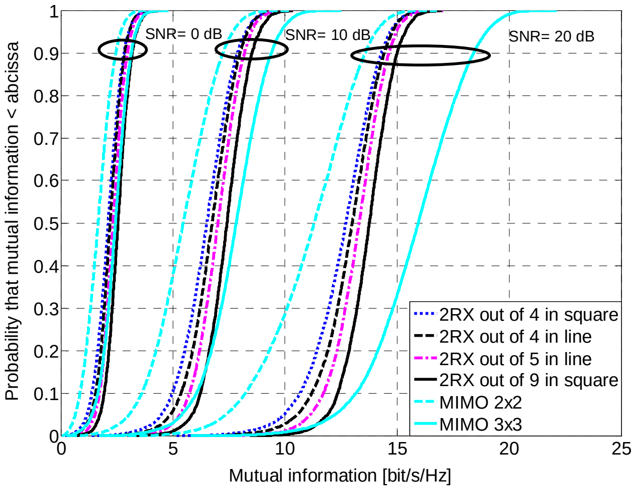

Fig. 3. MI obtained by selecting 2 RX out of *N*, with optimum capacity criterion and the ideal switching network.

Case 2

Fig. 4 shows the MI obtained by selecting 3 RX out of *N* with OCC and the ideal switching network together with the MI of traditional 3x3 and 4x4 MIMO at SNR = 0, 10 and 20 dB. The maximum MI increase at 10% probability, as compared to traditional 3x3 MIMO, is 55.8%, and is obtained with the 9 element sub-array at SNR = 0 dB. The minimum MI increase at the same probability level is 7.3%, and is obtained with the 4 element in line sub-array at SNR = 20 dB. One can notice that the MI increase is lower when selecting 3 elements out of *N* than 2 elements out of *N*, as reported in [6].

Case 3

The MI obtained by selecting 2 RX out of *N* available antennas with SNRC and the ideal switching network as well as the MI of traditional 2x2 and 3x3 MIMO are plotted at SNR = 0, 10 and 20 dB in Fig. 5. The maximum MI increase at 10 % probability, as compared to traditional 2x2 MIMO, is 116.6% and is obtained with the 9 element sub-array at SNR = 0 dB. The minimum MI increase at the same probability level is 8.8% and is obtained with the 4 element in line sub-array at SNR = 20 dB. Similarly to the results reported in [3] and [6], it is seen that the SNRC leads to about the same MI as OCC at low SNR but its performance decreases when the SNR increases.

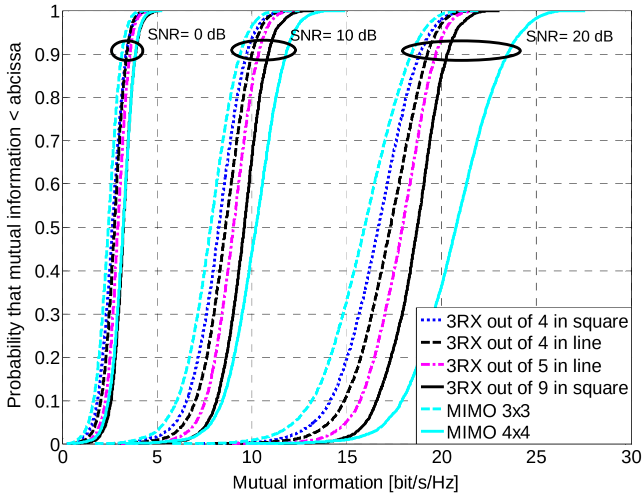

Fig. 4. MI obtained by selecting 3 RX out of *N*, with the optimum capacity criterion and the ideal switching network.

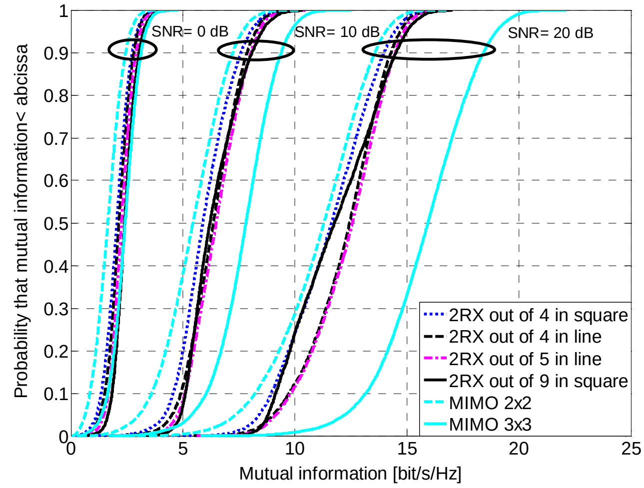

Fig. 5. MI obtained by selecting 2 RX out of *N*, with the SNR criterion and the ideal switching network.

Case 4

Fig. 6 shows the MI obtained by selecting 2 RX out of *N* available antennas, with the SNRC and the realistic switching network together with the MI of traditional 2x2 and 3x3 MIMO at SNR = 0, 10 and 20 dB. It can be seen that at most of the probability levels, for all sub-array shapes, the MI of antenna selection configurations is lower than the one of traditional 2x2 MIMO. The maximum MI increase at 10% probability, as compared to traditional 2x2 MIMO, is only 11.5%, and is obtained with the 4 element in line sub-array at SNR = 0 dB. The minimum MI increase (which is actually a decrease) at the same probability level is -11.6% and is obtained with the 9 element sub-array at SNR = 20 dB.

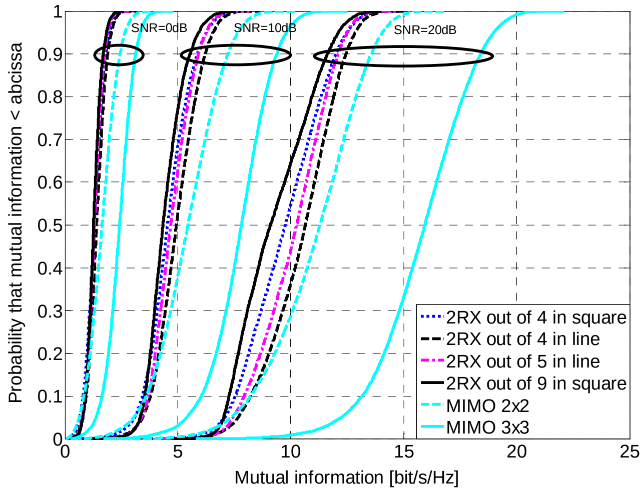

Fig. 6. MI obtained by selecting 2RX out of N, with the SNR criterion and the realistic switching network.

B. General comments

In all cases, regardless of the switching network and criterion, it was noticed that for the same number *N* of available antennas, the MI increase obtained by selecting 2 elements out of *N* is higher than the one obtained by selecting 3 elements out of *N*. In addition, it was found that the antenna selection performed at TX leads to about the same mean MI as antenna selection at RX. Nevertheless, at 10% probability a slight variation can be noticed, with a maximum MI difference of about 20%.

With the ideal switching network:

The sub-array which leads to the maximum MI increase is the 9 element in square, followed by the 5 elements in line, the 4 elements in square and the 4 elements in line. Furthermore, it was noticed that for all combinations the MI increase is higher at low probability level than at high probability level. The mean MI obtained with ideal switching network is close to the one reported in [6] for independent and identically distributed (i.i.d.) complex Gaussian variables with zero mean and unit variance. This was expected since the mean MI of the traditional MIMO used in this work is close to the one of i.i.d. complex Gaussian variables with zero mean and unit variance [8].

With the realistic switching network:

With OCC, the antenna selection of 2 elements outperforms traditional 2x2 MIMO only at low probability level and only for some sub-arrays. At 10% probability, the maximum MI increase obtained by selecting 2 antennas is only 18.3%. In a large majority of cases the MI obtained by selecting 3 elements is lower than the MI of traditional 3x3 MIMO. At 10% probability, the maximum MI increase obtained by selecting 3 antennas, is only 1%. With SNC, for all sub-array shapes and at all probability levels, the MI obtained by selecting 3 elements out of *N* is lower than the MI of the traditional 3x3 MIMO.

In most of the cases, at low SNR, the sub-array which maximizes the MI is 4 elements in line, followed by 5 elements in line, 9 elements in square and 4 elements in square. At high SNR, the order is the same as with the ideal switching network.

V. CONCLUSIONS

The performance of several MIMO antenna selection configurations with 2 and 3 selected elements out of *N* available antennas have been studied and compared to the traditional 2x2 and 3x3 MIMO, based on 60 GHz MIMO channel measurement data. With lossless switching network the mean MI are close to those found in the literature for antenna selection with i.i.d. complex Gaussian variables with zero mean and unit variance. At low SNR, the maximum SNR criterion leads to about the same MI increase as the optimum capacity criterion, but at high SNR maximum SNR criterion leads to lower MI, as reported in the literature. In the best case the MI obtained by selecting 2 elements out of 9 is about 127 % higher than the one of traditional 2x2 MIMO and is even higher than the MI of traditional 3x3 MIMO. However, when considering a realistic switching network, the performance decreases drastically: the mean MI of MIMO antenna selection with 2 and 3 selected antennas out of *N* is always lower than that of traditional 2x2 and 3x3 MIMO, respectively. With the realistic switching network, at 10% probability, the MI of MIMO antenna selection with 3 selected elements out of *N* always leads to lower MI than traditional 3x3 MIMO. It is shown that the switching network is a crucial issue in the implementation of antenna selection at 60 GHz. Furthermore, it is seen that in some cases, for the same number of RF chains, it can be more beneficial in term of mutual information to use traditional MIMO than MIMO antenna selection.

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