Degradation of MIMO-capacity due to correlation and efficiency of practical antennas

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1. Introduction

Handheld terminals such as mobile phones incorporate more and more multimedia functionality. This is a challenge for the terminal designers, since higher download speed is demanded. Therefore, a lot of research effort is currently spent on approaches to enhance download speed. One approach is to use multiple antennas on both the transmitting and receiving sides. If there are M antenna ports on the transmit side and N on the receive side, there will be MxN signal channels through the multipath environment, thereby allowing for higher data speed than if only one single channel is used. This is commonly referred as a MIMO-system. Multipath environments can be emulated in a reverberation chamber and hence the performance of a MIMO system can be measured there [1].

It is not obvious how to design good antennas for MIMO systems, since classical array theory can not be used. The maximum available capacity of the MIMO antenna system in an isotropic Rayleigh environment can in principle be calculated and used as a cost function in the optimization process of the antenna. However, most antenna engineers do not have any feeling for how to optimize the MIMO capacity and can not give a good starting point for the optimization process. Hence, it will be useful to find how classical antenna performance parameters like radiation efficiency and mutual coupling affect the MIMO-capacity, as shown initially in [2] by characterization both in reverberation chamber and by simulation. The correlation between the antenna ports in the multipath environment also affect the performance but was shown to be a minor effect compared to the radiation efficiency. The reverberation chamber has also been used to characterize the MIMO antennas in [3] and [4]. The purpose of the present paper is to compare the performance of three different practical linear MIMO arrays, each with 4 radiating elements, but having different element spacing. Previously, a circular array of monopoles was studied for different element spacing in [2].

2. Definitions used here

To understand the properties of the antenna as part of a MIMO-system, it is convenient to factorize the efficiency of the antenna in several subefficiencies, which can be interpreted physically, and then to calculate the capacity degradation due to each subefficiency. The radiation efficiency of a single port antenna is caused by losses in the materials of which the antenna is made, and it is common to include also losses in neighbouring objects such as head phantoms, if present. An additional efficiency contribution is the mismatch factor, and the product of the radiation efficiency and the mismatch factor is normally called the total radiation efficiency. The corresponding efficiency of a single port in a MIMO array is the *embedded element efficiency*. This is the radiation efficiency of each port when all the other ports are terminated. Hence, it includes everything such as mismatch and losses. The latter factor will also include dissipation in the loads on the neighbouring ports (an effect of mutual coupling), in addition to the losses in the materials of which the antenna is made, and in adjacent objects such as a head phantom. The *mismatch efficiency* is simply the contribution to the embedded element efficiency due to reflection on the considered port (when the others are terminated). The *coupling efficiency* can for a four port antenna be written in terms of the S-parameters, and for port 1 it becomes:

$e_{\text{coupling}} = 1 - |S_{21}|^2 - |S_{31}|^2 - |S_{41}|^2$, see equation (58-15) in [5]. The correlation between the ports of a 2-port MIMO array can be characterized in terms of a *correlation efficiency* in the same way as the reduction in diversity gain, see equation 23 in [2]. This can be calculated approximately as: $e_{\text{corr}} = 1-|\rho|^2$, where ρ is the correlation between the ports. The generalization to a multiport antenna is not known, although it could intuitively be written as: $e_{\text{corr}} = 1 - |\rho_{21}|^2 - |\rho_{31}|^2 - |\rho_{41}|^2$. However, it is known and will also be shown later in this paper that correlation only plays a minor role for the degradation of MIMO-capacity compared to the degradation due to radiation efficiency.

3. Measurements

All measurements were done in the high performance reverberation chamber from Bluetest AB, except for the couplings between the ports which were measured in free space by using a network analyzer.

The chamber creates an isotropic fading environment from which the channel matrix can be obtained. The channel matrices are first normalized to the average power level measured on a separate one-port reference antenna (with known efficiency) located somewhere else in the chamber. The maximum available MIMO-capacity can then be calculated directly from these normalized channel matrices by using an extended version of Shannon's formula:

$$C = \log_2 \det(\boldsymbol{I}_M + \frac{SNR}{3}\boldsymbol{HH}^*) \quad (1)$$

This measurement technique has been validated against simulations in [1]. The embedded element efficiencies are readily obtained by comparing the average signal levels on the port on the MIMO array and the port on the reference antenna. We can use the S-parameters measured between the ports when the antenna is located in free space to determine the coupling efficiencies and the mismatch factor on each port, and thereby we can find the remaining subefficiency due to ohmic losses as the ratio between the measured embedded element efficiency (total radiation efficiency) and the coupling efficiency, in order to find the relative importance of these factors.

The measured antennas are shown in figure 1. All of them are designed and manufactured by Rayspan Corporation in California. In principle, they are 4-element monopole antennas with different spacing between the elements. The spacing between the elements is λ/2, λ/4 and λ/6, respectively, at 2.5 GHz. Those are reasonable distances for bigger devices such as portable computers, but not for handheld devices such as mobile phones. However the conclusions presented later in this paper is still of interest for those devices.

The embedded element efficiency is plotted in figure 2. Notice that the efficiencies are similar for all four ports when the separation between the elements is large. When the spacing is decreasing, we can clearly see that the two elements in the middle have significantly lower efficiency. This is because they couple strongly to two adjacent elements. The edge elements only couple strongly to one element.

The degradation of capacity due to the efficiencies is found by assuming that the signal to noise ratio is decreasing, i.e. the noise is kept fixed, and the signal power is decreased by the value of the efficiency degradation. This capacity degradation can be found directly from figure 3. The actual numerical calculations in this paper are simplified a bit, by assuming a linear shape of the curve around the 15 dB SNR point. This is a reasonable approximation for small deviations from the 15 dB point. The measurements are summarized in table 1. When the antenna elements are moving closer to each other, we see that the coupling efficiency is decreasing, as expected. The correlation also increases when the antenna elements are located closer to each other.

The interesting thing to notice is that the correlation efficiency always is much higher that the coupling efficiency. Notice that this is also true for the antenna with the smallest spacing between the elements. We can conclude that it is more important to focus on getting a good embedded element efficiency of the antenna than to worry about the correlation, for most practical antennas. It is also known from [6] that the correlation between two closely spaced parallel dipoles is not too bad. This can be understood easily, since when one of the dipoles is excited, then the other acts as a reflector. The embedded radiation pattern for the dipoles will thus be completely different which gives a low correlation. On the other hand, they will couple strongly to each other since they are close and thus make the correlation efficiency low.

4. Conclusions

The figure of merit of a multiport antenna in a MIMO system is the maximum available capacity as a function of the SNR. This capacity should be optimized when a modern wireless terminal such as mobile phone is designed. We have presented measurements of three practical linear MIMO arrays in a reverberation chamber. The results confirm that the embedded element efficiency is the main factor reducing the maximum available capacity, and that the correlation between the ports is a minor contributor.

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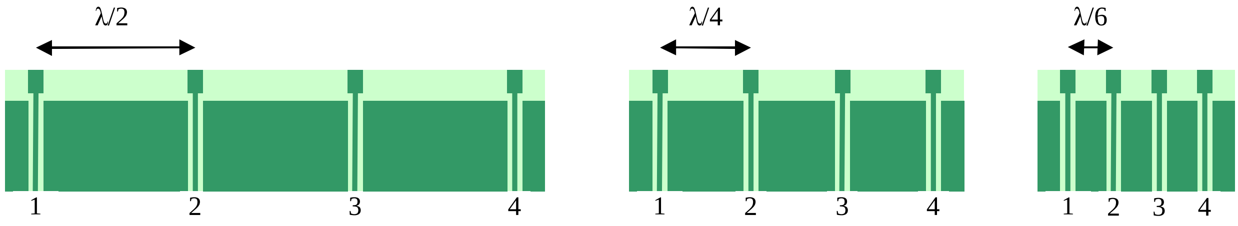

Figure 1: The antennas measured. From left, antenna X, Y and Z.

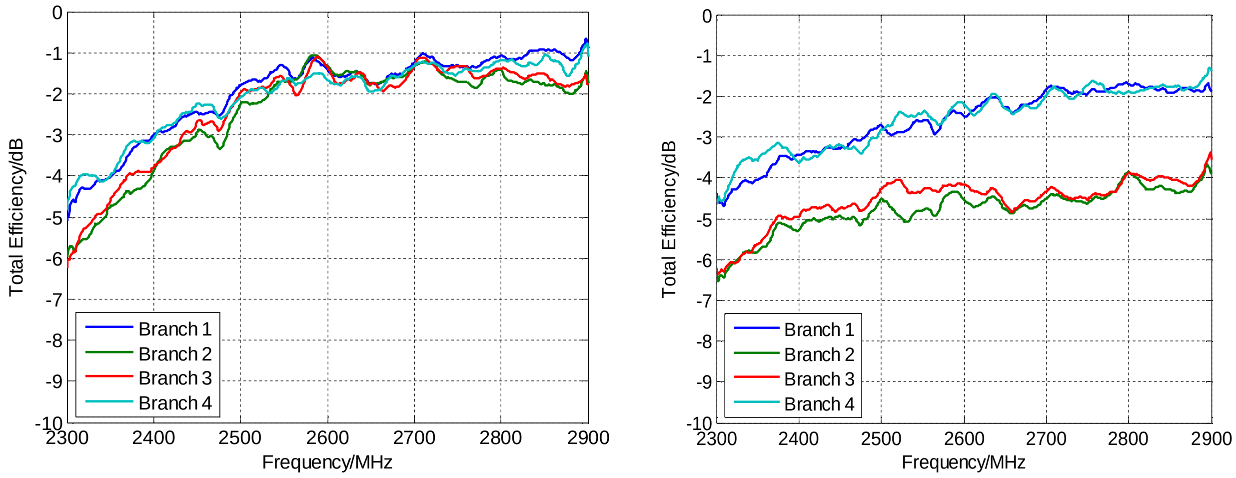

Figure 2: Embedded element efficiency for antenna X (left graph) and antenna Z (right graph).

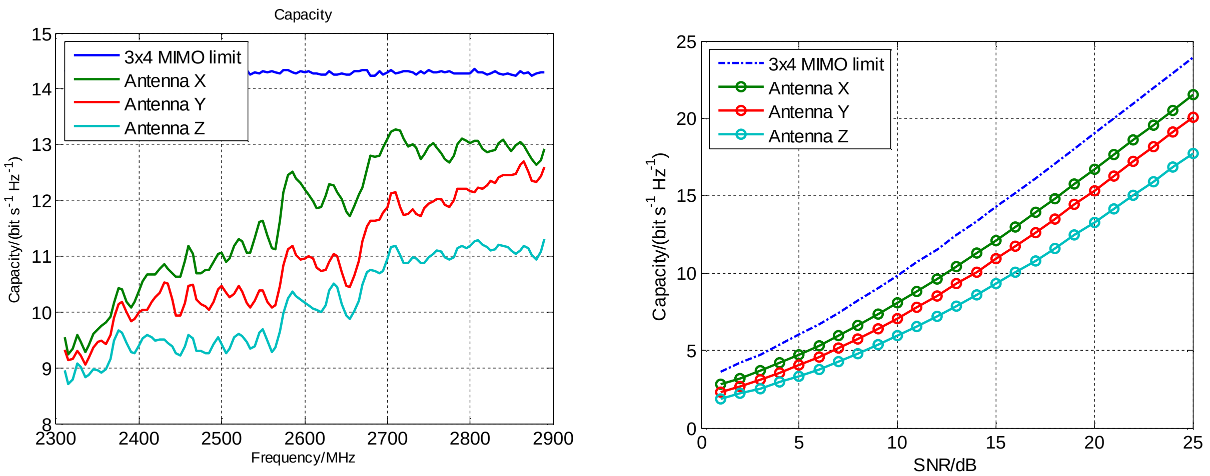

Figure 3: The measured capacities

TABLE I
MEASURED DATA

	Antenna (2.5 GHz)		
	X	Y	Z
Average mismatch eff. [dB]	-0.2	-0.3	-0.2
Average radiation eff. [dB]	-1.0	-1.2	-2.1
Average coupling eff. [dB]	-0.5	-1.5	-1.7
Average embedded element eff. [dB] (sum of above)	**-1.7**	**-3.0**	**-4.0**
Average correlation	0.051	0.154	0.329
Correlation efficiency [dB]	-0.01	-0.10	-0.50
Theoretical maximum capacity [bps/Hz]	14.26	14.26	14.26
Measured capacity at 15dB SNR [bps/Hz]	12.12	10.91	9.29
Cap. red. due to average mismatch eff. [bps/Hz]	0.213	0.213	0.121
Cap. red. due to average coupling eff. [bps/Hz]	0.415	1.293	1.272
Cap. red. due to average radiation eff. [bps/Hz]	0.887	0.979	1.572
Cap. red. due to meas. errors and correlation. [bps/Hz]	0.623	0.866	2.009
Cap. red. due to correlation efficiency [bps/Hz]	0.010	0.087	0.366