

A Fair Comparison of Virtual to Full Antenna Array Measurements

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Abstract—Massive multiple-input multiple-output (MIMO) channel measurements are often obtained using virtual antenna arrays for complexity reasons. In this approach, a single antenna element is sequentially re-positioned to virtually form an antenna array in space. As a consequence, there are no mutual coupling effects when measuring with a virtual array. We perform real-world outdoor to indoor MIMO channel measurements with both, a virtual array approach and a full array approach, for various antenna spacings. From the obtained results, we observe that a spacing of a half-wavelength does not lead to the best match between the two approaches. We conclude that the deviation mainly originates from mutual coupling effects and quantify the difference in terms of error in channel gain.

Index Terms—massive MIMO, virtual array, mutual coupling

I. INTRODUCTION

The idea of massive multiple-input multiple-output (MIMO) systems for future mobile communications systems has gained a lot of interest in the past years [1], [2]. By scaling up a MIMO system in terms of number of antennas, high gains in sum spectral efficiency for multi-user transmissions with comparable low computational complexity and high energy efficiency are expected [3]. However, these desirable advantages are only achievable if the wireless channel offers so called favorable propagation conditions [1]. To investigate if massive MIMO systems show gains in real-world wireless channels, measurement campaigns with large antenna arrays were performed [4], [5]. As hardware complexity is high when MIMO channel measurements are performed with large antenna arrays, often the concept of a virtual antenna array is exploited [6]–[10]. In a virtual array approach, in the simplest case, a single antenna element is mounted on a mechanical guide system and is connected via a single cable to a single channel transmitter. By sequentially re-positioning this single antenna element in space and transmitting sounding sequences at each position, a potentially large antenna array is virtually formed in space. With this measurement methodology, the

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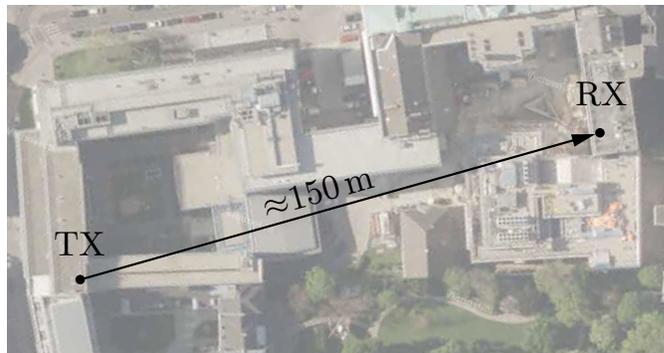


Fig. 1: Aerial photo of the measurement scenario [13]. The antenna array at the transmitter is outdoors on a rooftop. The receive antenna is indoors.

hardware requirements are dramatically reduced. Although the hardware complexity is significantly less compared to a full array at one point, e.g., antenna array, cabling and multi-channel transmitter, also other hardware complexity is added with this methodology, e.g., a mechanical guiding system and frequency synchronization.

Time-invariance of the measurement equipment and the wireless channel as well as phase noise are troublesome in (virtual) MIMO channel sounding, as already experienced by others [11], [12]. Since the antenna positions within the virtual array are exploited consecutively in time for channel sounding, simply because re-positioning of the antenna cannot be done infinitely fast, the whole measurement setup needs to be time-invariant. This not only means that the wireless channel, which is the actual body of investigation, has to be static, but also the transmitter and receiver hardware have to be time-invariant.

Another issue of virtual array measurements is, that the wireless channel from the transmit antenna to the receive antenna is measured in the absence of all other transmit antennas. This is an inherent problem of virtual array measurements that becomes significant, when neighboring transmit antennas influence each other, that is, in the case of mutual coupling [14]–[16]. Previous works show, that mutual coupling has a significant impact on channel capacity, especially for small antenna separation [17]–[19]. If a wireless channel is measured with a virtual array, the measurement results do

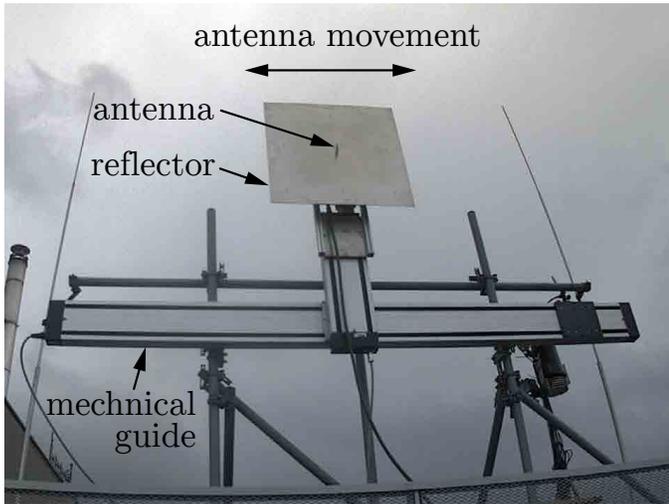


Fig. 2: The mechanical setup at the transmitter for a virtual array measurement. The setup for a full array measurement looks the same, but with four antenna elements mounted on the reflector.

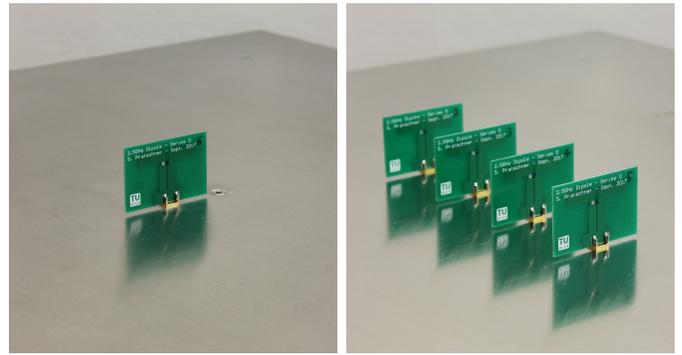
not include effects of mutual coupling. In case the mutual coupling of the antenna array is known, a coupling model can be applied on the measured channel to include mutual coupling effects [16], [19]. However, obtaining knowledge about the mutual coupling for arbitrary antenna elements and array geometries is not straight forward.

It is known, that the coupling function is zero at a half wavelength antenna spacing for isotropic elements [20]. This is also the element spacing employed for most of the previously mentioned channel measurements. However, if non-isotropic antenna elements are exploited, this element spacing is not necessarily ideal, in the sense that mutual coupling is present.

Contribution: We perform real-world outdoor to indoor measurements with full arrays as well as virtual arrays with different inter-element spacings. The measurements are performed such that the obtained results are comparable with each other in a fair way. We show, that the measured channel gain is different for these two cases, depending on the element spacing. From this observation we conclude, that antenna elements within an array influence each other. Accordingly, mutual coupling is present, also for a spacing of half a wavelength. Depending on the type of antenna elements and the array geometry, this effect leads to a significant deviation in received signal power between virtual arrays and full antenna arrays.

II. MEASUREMENT SETUP

We consider a MIMO downlink scenario, where the base station is equipped with a possibly large antenna array of N_T antennas, and a user equipment with a single antenna. Our setup consists of an antenna array with $N_T = 4$ antennas at the transmitter side, that is outdoors on a rooftop, and a receiver with a single antenna which is located indoors in an office environment, see Fig. 1. The transmitter and



(a) Virtual array.

(b) Full array.

Fig. 3: Printed dipole antennas mounted on an aluminum reflector. (a) Single dipole antenna for virtual array measurements. (b) A full array of four dipole antennas with a spacing of exemplary $d = 0.5 \lambda$.

receiver are separated by approximately 150 m. We employ a center frequency of 2.5 GHz, which corresponds to a free-space wavelength of $\lambda \approx 120$ mm.

The mechanical setup at the transmitter side is shown in Fig. 2. An electrically driven mechanical guide allows for fast horizontal re-positioning of the transmit antenna (including the reflector). With this setup, a virtual uniform linear antenna array with almost arbitrary antenna element spacing and antenna count N_T can be formed. Fig. 2 shows the case of a virtual array with a single antenna element. The setup for a full array looks similar. In the latter case, there are N_T antenna elements mounted through the reflector and connected to the transmitter via N_T cables. In both cases, the antenna element itself is a printed dipole antenna similar as in [21] which includes a symmetry transformer. The printed circuit board design of antennas offers low cost elements with very high similarity. This allows the realization of a large uniform antenna array. The dipole element is mounted in front of a large quadratic aluminum reflector plate of $6.25 \lambda \times 6.25 \lambda$, see Fig. 3. For virtual array measurements, a single antenna element is screwed through the reflector as shown in Fig. 3a. For full array measurements, N_T dipole antennas are attached through the reflector plate, see Fig. 3b. With this antenna design, a directive antenna pattern with a gain of 6 dBi and a very high front-to-back ratio of approximately 30 dB is obtained. By this, the influence of the mechanical guiding system and the framework at the backside of the reflector is negligible.

The receive antenna is mounted indoors on an XY positioning table in an office environment. To infer the mean capacity of this scenario, we obtain independent channel realizations by moving the receive antenna to 49 different positions [22]. These positions are chosen to lie on a quadratic grid of 7×7 with a large spacing of 0.6λ to obtain uncorrelated measurements.

A. Transmit Signal

As transmit sequence, an orthogonal frequency division multiplexing (OFDM) signal is used. Similar to [23], Newman phases were applied to obtain a transmit signal with low crest factor. The transmit signal is described by

$$x(n) = \text{Re} \left(\sum_{k=-K/2}^{K/2-1} e^{-i2\pi k \frac{n}{N}} e^{i\pi \frac{k^2}{K}} \right), \quad (1)$$

where $n = 0, \dots, N-1$ is the time index and K is the number of subcarriers. We employ a subcarrier spacing of 15 kHz and $K = 100$ subcarriers. This leads to a total bandwidth of $100 \times 15 \text{ kHz} = 1.5 \text{ MHz}$. Each transmit sequence consists of a total of 101 symbols that are transmitted consecutively without zero padding or cyclic prefix (CP). At the receive side, the first symbol of the entire sequence is interpreted as CP and discarded. Assuming the channel delay spread to be shorter than the symbol duration, the remaining 100 received symbols are identical up to additive noise. By averaging them, a processing gain of 20 dB is obtained. As the duration of one symbol is $1/15 \text{ kHz} \approx 66.67 \mu\text{s}$, the total transmission time per sequence is 6.7 ms. This transmission sequence is transmitted for each position within a virtual array. For a measurement with a full array, the sequence is transmitted once per antenna, consecutively in time, that is, a time division duplex channel sounding approach is employed.

B. Synchronization and Measurement Accuracy

The Vienna MIMO testbed [22] employs GPS disciplined Rubidium frequency standards together with hardware based timing synchronization units [24] at the transmitter and at the receiver. This setup allows triggered measurements with a synchronization error of $\pm 10 \text{ ns}$. As explained in the previous section, we employ a whole OFDM symbol with a duration of approximately $66.67 \mu\text{s}$ as CP. Therefore, the timing synchronization of our measurement setup is orders of magnitude better than the CP length. As the channel delay spread is also much shorter than the CP duration, our measurements do not suffer from inter-symbol interference.

Our Rubidium standards have a frequency accuracy of $\pm 5 \cdot 10^{-11}$. The 10 MHz output signals from the frequency standards are fed to the local oscillators (LO), which generate a 2.5 GHz continuous wave signal. As the LOs are implemented as a phase locked loop (PLL), they basically multiply the input frequency with a factor of 250. In the worst case, the frequency standard at the transmitter and the frequency standard at the receiver differ by 1 mHz, which corresponds to $10 \cdot 10^{-11} \times 10 \text{ MHz}$. The difference at the frequency of interest is then $\Delta f = 250 \times 1 \text{ mHz} = 0.25 \text{ Hz}$. This absolute frequency offset is in the order of a few ppm of the subcarrier spacing. Therefore, effects, such as inter-carrier interference, originating from carrier frequency mismatch are small compared to the total measurement accuracy [25].

The frequency offset of 0.25 Hz corresponds to a phase drift of $\frac{d\phi}{dt} = 2\pi\Delta f \approx 90^\circ/\text{s}$. Given that re-positioning the antenna element of a virtual array takes a few tenths of a

second, the phase change between transmitter and receiver between two consecutive measurements is several degrees. For a large number of antennas N_T , which corresponds to many positions in the virtual case, the situation becomes even worse, as the measurement time scales linearly with N_T . However, for a multiple-input single-output (MISO) system with channel vector $\mathbf{h} \in \mathbb{C}^{N_T \times 1}$, this phase error has no impact on the channel capacity or channel gain $\|\mathbf{h}\|^2$.

Using channel gain as a metric, amplitude calibration of the measurement setup is an important aspect. After calibration, we verified that the time drift of the amplitude is negligible compared to the signal level by setting up an directional radio link between transmitter and receiver.

III. EXPERIMENT AND RESULTS

A. Experiment

We compare virtual array measurements to full array measurements. As our hardware consists of a four channel transmitter, we choose $N_T = 4$ for our measurement. Although this number of antennas is not considered as massive, mutual coupling between neighboring antenna elements will occur also if the number of antennas is increased. We compare inter-element spacings of $d \in \{0.1, 0.3, 0.5, 0.7, 0.9\} \lambda$. For the full array measurement, the antenna array is not moved during the measurement. For the virtual array measurement, the antenna element's positions are chosen to exactly coincide with the elements' positions of the corresponding full antenna array. By this measurement design, we ensure that observed effects originate only from the antenna spacing, rather than their absolute position. To obtain an estimate for the outdoor-to-indoor scenario mean, that is, to average channel realizations, the indoor receive antenna is re-positioned 49 times. For a virtual array measurement, the receive antenna is moved to exactly the same 49 positions for each of the four transmit antenna positions. We obtain channel estimates from the received signals by least squares channel estimation.

There are several effects that lead to a deviation between the channel measurements carried out with a virtual array compared to those carried out with a full array, for example:

- *The size and position of the reflector plate:* While there is only one antenna element in the center of the reflector, there are four elements on the reflector in the case of a full antenna array. While the antenna element in the virtual array is always perfectly in the center of the reflector, elements of the full array are not in the center of the reflector. Therefore, the individual radiators in the full array will behave slightly different compared to the single element in the virtual array. To keep this difference small, we used a reflector that is large compared to the wavelength.
- *The time variance of the measurement setup:* As already mentioned, the whole measurement setup as well as the wireless channel under investigation have to be time-invariant to allow for virtual array measurements. While the time-invariance of the measurement setup is controllable and verifiable up to a certain extend, the real-world

wireless channel cannot be controlled. Any change of the wireless channel during the measurement with virtual arrays and full arrays causes an error in our channel measurements. We carried out all measurements twice, consecutively in time, to verify that the channel does not significantly change with time.

- *The amplitude calibration of the four transmitter channels:* In the case of a full array measurements, the four transmit antennas are connected to the four transmitter channels. When measuring with a virtual array, the single antenna element is connected to the first transmitter channel. Therefore, a deviation between the transmitter channel amplitudes leads to an error in our measurements. Consequently, we used equal hardware and calibrated the transmit channels to make sure that the deviation is low compared to the transmit power level.
- *Mutual coupling between the antenna elements:* As it is well known, two closely spaced antennas alter each other's current distribution when excited. This mutual coupling effect leads to a change in radiation pattern and input impedance of the antenna elements. Since there is only one radiating element in a virtual antenna array, there are no mutual coupling effects, opposed to the full array approach. As we minimized all other effects that lead to a difference between the virtual array and the full array, we conclude that the remaining difference is mainly caused by mutual coupling.

To investigate the strength of mutual coupling within the full antenna array, the scattering parameters of the array were measured with a network analyzer. The magnitude of the scattering parameter between the two middle antenna elements for different antenna separations d is shown in Fig. 4. As a reference, the scattering parameter magnitude between two thin half-wavelength dipoles in a side-by-side configuration from [26, p.476] are also shown as *theoretic* curve. Our employed printed dipole antenna is not a thin dipole, has a printed symmetry transformer included and is mounted in front of a metal reflector. Therefore, the measured curves does not show a perfect match with the theoretic result. Especially at 0.1λ the symmetry transformer seems to have a strong impact. Still, the measured mutual coupling is lower compared to the analytic solution for spacings larger or equal to 0.5λ . Please note, that the scattering parameter between two antenna elements indicates how much of the power radiated from one element is received by the other element. However, it was shown in [20] and [14], that only the mutual resistance between the antenna elements contributes to the mutual coupling.

B. Results

As a metric that is independent on signal to noise ratio (SNR), we consider the relative error of the channel gain. This error is calculated between the channel vector obtained from virtual array measurements \mathbf{h}_{virt} and the channel vector obtained from full array measurements \mathbf{h}_{full} . Here, the channel vectors are obtained by averaging the estimated channel in frequency domain, that is, over subcarriers. Exploiting the

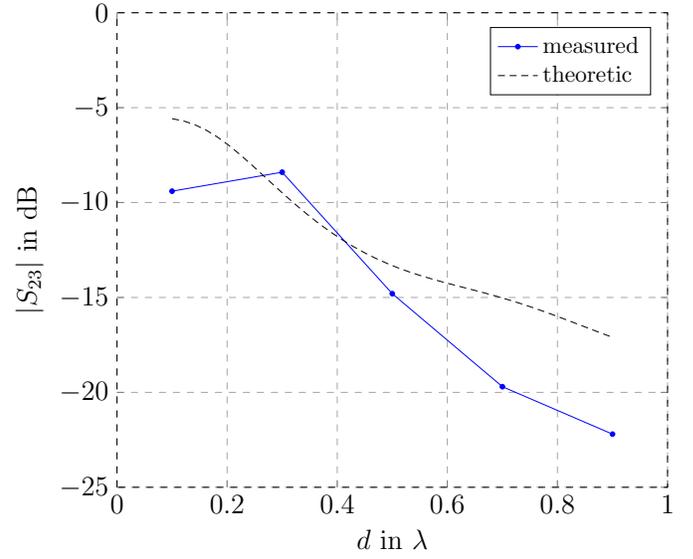


Fig. 4: S-parameter magnitude between the two middle antenna elements 2 and 3.

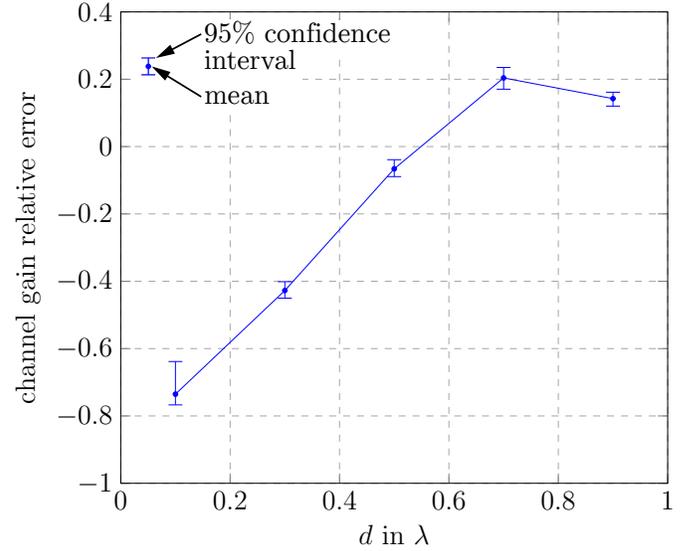


Fig. 5: Error in estimated channel gain obtained with a full array, relative to the channel gain obtained with a virtual array.

virtual channel measurement as reference without mutual coupling, the relative error in channel gain is given by

$$\mathbb{E} \left\{ \frac{\|\mathbf{h}_{\text{full}}\|_2^2 - \|\mathbf{h}_{\text{virt}}\|_2^2}{\|\mathbf{h}_{\text{virt}}\|_2^2} \right\}, \quad (2)$$

where the expectation is taken with respect to channel realizations, that is, receiver positions. The relative error in channel gain over antenna separation d is shown in Fig. 5. We observe, that for spacings d lower than 0.5λ the relative error in channel gain is negative and high in magnitude. That means, the received power is reduced when using a full antenna array compared to a virtual array, for the same transmit power. While this error reduces when the spacing is increased, as the

mutual coupling decreases with separation, still, at $d = 0.5 \lambda$ the relative error in channel gain is -6.6% . As previously mentioned, a mutual coupling model, such as [16], [19], can be applied to include mutual coupling effects in the virtual array measurements.

As the receiver noise is independent of the actual antenna configuration, the relative channel gain error does not depend on SNR. However, the result needs to be put into perspective. While for a high SNR the error in estimated channel gain does not have a large impact on channel capacity, the error in channel capacity is relatively higher at a low SNR. For example, the relative error in channel capacity between a channel measured with the full array compared to the channel measured with the virtual array at $d = 0.5 \lambda$ is -1.2% for an SNR of 30 dB, but -3.9% at 5 dB SNR. These SNR values correspond to the virtual array case, averaged over receive positions. This result is in accordance with [20], where it is explained that the coupling function is zero at a spacing of half a wavelength only for isotropic radiators. For any other antenna element, this is not exactly true. Which separation is optimal, in the sense, that no coupling effects occur, depends on the utilized antenna element.

IV. CONCLUSION

Real-world outdoor to indoor measurements with virtual antenna arrays, as well as with full antenna arrays, were performed for different antenna spacings. Measurement results show, that channel gain and capacity obtained from a virtual array and a full array are different, especially for small element spacings. We conclude that this difference originates in mutual coupling. Results are evaluated in terms of relative error of channel gain, which is independent of measurement SNR. We conclude, that a spacing of 0.5λ is not the ideal spacing for a virtual array measurement as the difference to the full array measurement is not zero at this point. This deviation comes from the fact, that the employed antenna elements are not isotropic. The error being made when sounding a channel with a virtual array highly depends on the antenna elements.

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