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Experimental Evaluation of MIMO Terminals with User Influence in OTA Setups

Wei Fan, Pekka Kyösti, Lassi Hentilä, and Gert F. Pedersen

***Abstract*—User influence, together with propagation environments and antenna designs, determines how well MIMO terminals operate in true usage conditions. In this paper, we investigate to what extent the user influence affects the performance of a realistic MIMO terminal under various reproduced spatial channel models in a practical 3D multi-probe anechoic chamber (MPAC) setup. A terminal mock-up, operating at 2.55 GHz, together with a realistic user phantom was used, and channel models with different spatial and polarization profiles, DUT with different operation modes and orientation angles were tested.**

***Index Terms*—Anechoic chamber, MIMO OTA testing, User influence, MIMO performance evaluation**

I. Introduction

User influence, especially the hand and head effect, is commonly present in the vicinity of every terminal in true usage conditions [1]–[3]. Extensive research work has been reported to assess the user influence on antenna radiation performance, e.g. radiation efficiency and mismatch loss [1], [3]. It has been recognized that the antenna radiation performance can be greatly degraded in the presence of user influence. In the CTIA over-the-air (OTA) testing of single antenna system, antenna radiation performance in terms of total radiated power (TRP) and total isotropic sensitivity (TIS) is required to be measured in free space and with phantoms [4].

As an essential feature in fourth generation (4G) LTE and wireless local area network (LAN) communication systems, multiple antenna technology is seen to deliver high data-rate, good signal coverage and reliable link connection [5]. Antenna design and propagation channels are the two key parameters that ultimately determine the multiple-input multiple-output (MIMO) performance. As for antenna designers, their focus was primarily on counteracting the performance degradation introduced by user influence to optimize antenna efficiency [3], and therefore measurements of antennas typically focused on antenna radiation performance with various user interaction and mobile terminal usage [1]–[3]. The performance of multiple antenna systems should be assessed in realistic propagation channels with true user terminal utilization (i.e. with user influence present) [1]. However, only few results have been reported to deal with this aspect. An extensive channel measurement campaign in urban scenarios was reported in [6] to investigate the effect of user on measured channel capacity. In [2], a composite channel method was proposed and validated to incorporate channels with user interaction.

OTA testing of multiple antenna system presents many advantages over field trials, e.g. repeatability, reliability, and measurement efficiency. Recently, the multi-probe anechoic chamber (MPAC) method has been selected in CTIA and 3GPP standardization [7]. With this method, realistic propagation environments in which the performance of the device is evaluated can be physically emulated in a controllable and repeatable manner [8]. Research work in MPAC setups has been limited to free space conditions. CTIA standard has set guidelines on user interaction with multiple antenna terminals, though no results have been reported [7]. In the literature, the impact of user influence on MIMO handset is typically investigated in field measurements, see e.g. [2], [6]. However, field trials are expensive, time-consuming, labour-intensive, and even impractical for some cases, e.g., high mobility scenario [9]. Worse still, field trials may be uncontrollable and unrepeatable due to the open air environment. Assessing the effect of user influence in MPAC has several advantages: 1) antennas are inherently included, without any cable connection 2) various interactions between device under test (DUT) and user phantom, e.g. grip style, orientation, and etc., can be evaluated in controllable and repeatable propagation environments. 3) arbitrary propagation environments can be reproduced.

II. Test equipment and setup

A. Introduction

An illustration of the measurement system is depicted in Figure 1. The system consists of a three-port vector network analyzer (VNA), four Propsim F8 channel emulators, an anechoic chamber, 32 dual-polarized OTA antennas, power amplifiers (PAs) and a DUT with two antennas. The VNA was connected to the DUT antennas via coaxial cables. The measurement campaign was carried out in a three dimensional (3D) MPAC setup. The test setup is detailed in Table I. Desired spatial channels were reproduced with channel emulators and multiple OTA antennas. Then the DUT was evaluated under the reproduced channel models under two conditions, in the free space and with the user influence.

1) DUT and user phantom: To investigate the user influence on realistic DUTs, a mock-up with two planar inverted F-antenna (PIFA) elements was designed, as shown in Figure 2. The two antennas, operating at 2.55 GHz, were separated around 0.5λ. The primary antenna is located on the lower left corner and placed parallel to the long edge of the board, while the secondary antenna is located on the upper right corner of

Wei Fan, and Gert F. Pedersen are with the Antennas, Propagation and Radio Networking section at the Department of Electronic Systems, Aalborg University, Denmark (email: {wfa}@es.aau.dk).

Pekka Kyösti, and Lassi Hentilä are with Keysight, Finland.

Pekka Kyösti is with center for wireless communications (CWC), Oulu university, Oulu, FI-90014, Finland.

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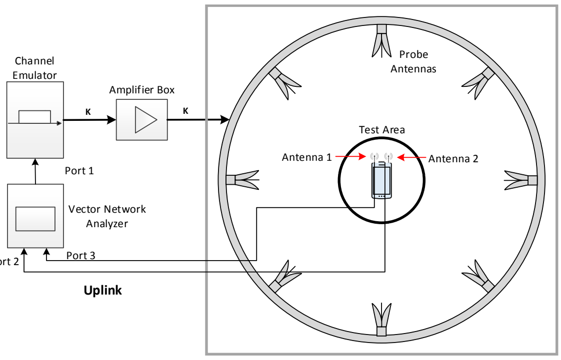

Figure 1. An schematic drawing of the measurement setup.

Table I
SETUP AND SPECIFICATIONS OF EACH COMPONENT IN THE MEASUREMENT SYSTEM

Component	Setup and specifications
VNA	The transfer function per DUT antenna was recorded, with the center frequency at 2.55 GHz and a span of 10 MHz. The output power and number of frequency samples were set to -15 dBm and 201, respectively. The intermediate frequency (IF) bandwidth was set to 10 KHz.
Anite Propsim F8 radio channel emulator	The prefaded signal synthesis (PFS) technique is used to map CIRs to multiple OTA antennas to reproduce the target channel models [8]. The DUT speed and center frequency were set to 30 km/h and 2.55 GHz, respectively.
DUT rotation	The DUT was rotated virtually at four angles (0^o, 90^o, 180^o and 270^o) in the horizontal plane. Note that the virtual rotation was realized via rotating the channel spatial profiles in the emulator, while the DUT was maintained static during measurements.

the board and placed orthogonal to the primary antenna. The isolation between the two antennas is around 15 dB at 2.55 GHz. Note that a third PIFA antenna on the mock-up was properly terminated by matching loads and was not used. The user phantom consists of two separate parts, a head phantom and a hand phantom, as shown in Figure 3.

2) Considered radio channel models: We attempted to evaluate the realistic MIMO mock-up under different propagation environments. More specifically, channel models with different spatial profiles, polarization characteristics and elevation profiles were targeted. We examine six representative 2D and 3D geometry-based stochastic channel models (GSCMs) [1],

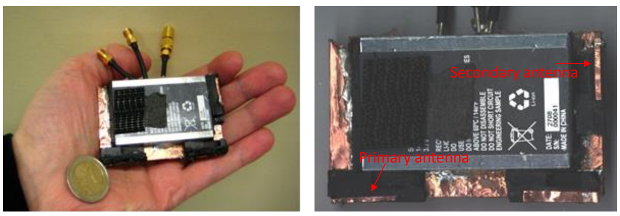

Figure 2. The mock-up (left) and antenna design on the mock-up (right).

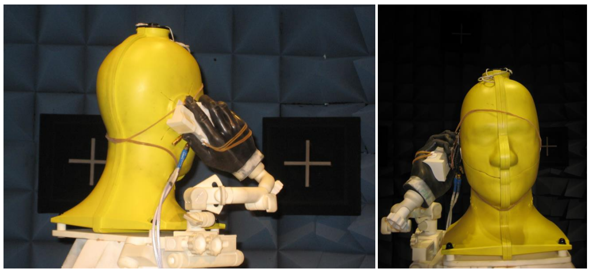

Figure 3. Photo of the mock-up phone with a SAM phantom head and hand.

where 3D channel models include:

A) 3D Laplacian-shaped vertically-polarized spatial cluster. Azimuth angle of arrival (AoA) and azimuth angle spread (ASA) are set to 0^o and 35^o, while elevation angle of arrival (EoA) and elevation angle spread (ESA) are set to 0^o and 20^o, respectively.

B) 3D Laplacian-shaped dual-polarized spatial cluster [10]. Same channel parameters as A are set, except that the cross polarization ratio (XPR) is set to 8 dB.

C) 3D vertically-polarized IMT-advanced UMi model.

As for the three 2D channel models, the same parameters as in the corresponding 3D model are set individually, except that elevation angles and elevation spreads are set to 0^o.

3) Operation modes: Two different operation modes were investigated, free space mode and user influence mode. The free space mode represents the case where no user phantom is present. This mode is generally assumed in the literature for MIMO OTA testing [7], [8]. As for the user influence mode, only talk mode where the user holds the DUT in the right hand, with the DUT pointing to the right ear was investigated [2], as shown in Figure 3. Note that the phantom head nose was pointing to AoA = 0^o for rotation angle 0^o. Furthermore, as the antenna performance depends highly on the DUT position, the mock-up was positioned to the same location and same orientation in both free space and user influence mode, to ensure that the performance discrepancies in two modes were only introduced by the effect of user influence.

4) Probe configuration: 32 dual-polarized Vivaldi antennas (i.e. 64 antenna ports) are used as OTA antennas, as illustrated in Figure 4. However, only a total of 32 channel emulator output ports are available with four Propsim F8 emulators. That is, a subset of OTA antenna ports need to be selected. For 3D vertically polarized channels, i.e. A and C, only 32 vertically-polarized antenna ports were selected; For 2D channel models, only the 16 OTA antennas (vertically-polarized or dual-polarized) on the azimuth ring with elevation 0^o were selected. As for channel B, only the dominant OTA antennas utilizing in synthesizing the channels (i.e. 3 on elevation ring $+30^o$, 7 on elevation ring 0^o and 3 on elevation ring -30^o) were selected, as depicted in Figure 4. All antennas on the DUT should be covered within the test zone. The test zone size is supported by the MPAC setup, if antennas on the DUT cannot distinguish the target and emulated channels. As antenna locations on the mobile terminals are typically unknown, it is often required that the terminal size should be smaller than the supported test zone in free space mode. There

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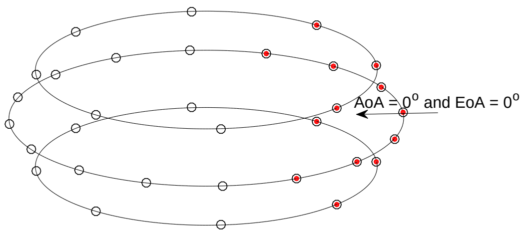

Figure 4. Probe configuration and selected OTA antennas for the channel B. Black circles denote the available OTA antennas and red solid circles represent the selected dual-polarized OTA antennas for channel B. The 3D probe configuration consists of three elevation rings, with 16 probes in elevation 0^o with 22.5^o azimuth spacing, 8 probes in elevation $+30^o$ with 45^o azimuth spacing and 8 probes in elevation -30^o with 45^o azimuth spacing.

is a concern whether phantom should be covered inside the test zone as well, together with the DUT, in the user influence mode. This problem was experimentally investigated in [11]. The impact of user phantom on the test zone size was shown to be not noticeable, since the deviations in terms of received power, branch power ratio, antenna correlation and measured throughput under the target and emulated channel models are not affected by the presence of the user phantom. That is, similar deviation levels were observed in the free space and in the presence of user phantom.

5) Measurement procedure: The measurement procedure is detailed in [7], and here we only summarize the key aspects. The channel emulators utilized in the measurement are capable of file-based emulation, where pre-stored CIRs can be emulated in a controllable way. 4 traces per wavelength is set as the sample density to obey the Nyquist sampling theorem when generating $h_k^{OTA}(t,\tau)$ for $k \in [1, K]$. In the measurement, $n_i = 1001$ traces were selected out of 10000 traces (i.e. with a step of 10 traces) to ensure that independent traces were recorded. We can then step the channel emulator to the selected trace and freeze the channel emulator. Note that in the frozen state, the radiated signals from probe antennas are static. A VNA is then utilized to measure the channel frequency response (CFR) of the selected trace. The measurement time per trace is around 25 ms. The CFRs for two antennas $h_1(f_k, t_i)$ and $h_2(f_k, t_i)$ were measured and stored during the frozen state, where f_k and t_i denote the frequency index and selected trace index, respectively, with $k \in [1, n_f]$ and $i \in [1, 1001]$. We can then repeat the procedure to record all selected traces. Note that in practical terminal performance measurements, we will replay all the CIR traces in a continuous mode (i.e. without the frozen state).

B. Data analysis

The average received power for individual DUT antenna can be calculated as:

$$P_j^{av} = \frac{1}{n_i \cdot n_f} \sum_i \sum_k |h_j(f_k, t_i)|^2, \quad (1)$$

where $j = \{1, 2\}$ denotes the antenna branch index.

Low channel correlation and low branch power ratio (BPR) are two factors that are commonly aimed for when designing MIMO terminals. The BPR can be defined as:

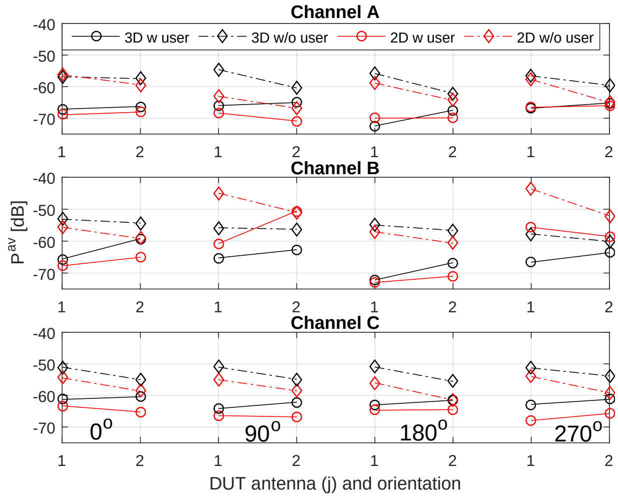

Figure 5. Average received power of individual antenna elements, for different channel models; at different user modes, rotations and antenna elements.

$$BPR = 10 \cdot \log_{10} (P_1^{av} / P_2^{av}) \quad (2)$$

Antenna correlation can be calculated as below:

$$\rho = \frac{\sum_{k=1}^{n_f} \text{corr}(\mathbf{h}_1(f_k), \mathbf{h}_2(f_k))}{n_f}, \quad (3)$$

where $\mathbf{h}_j(f_k) = \{h_j(f_k, t_i)\} \in \mathbb{C}^{1001\times1}$ is a complex vector that contains the 1001 traces recorded at frequency f_k for the j-th antenna for $j \in [1, 2]$. corr() is the correlation operator.

III. Measured Results

A. Average received power

Figure 5 shows average received power levels at DUT antenna 1-2 for the different channel models (subplot rows) and the four orientations (subsequent in each row) under the two operation modes. The power levels are generally lower in the user influence mode, compared to the free space mode for all channel models, since the power reduction is introduced by antenna radiation performance degradation (i.e. radiation efficiency, antenna mismatch and etc) and blockage effect in the propagation channel. The power reduction varies from around 0 dB (antenna element 2 under 2D Laplacian-shaped dual-polarized spatial cluster at orientation angle 90^o) and up to more than 15 dB (antenna element 1 under 2D Laplacian-shaped dual-polarized spatial cluster at orientation angle 180^o). For the user-effected MIMO antenna systems, the user together with the antenna is typically considered as one radiating unit [2], [11], [12]. The DUT antenna patterns with or without the user phantom might not be uniform (and possibly highly sensitive to orientations). Therefore, the power value per DUT antenna port might vary significantly with respect to orientations. The received power varies widely for channels with different spatial, polarization profiles and operation modes. We also notice that the power levels under multi-cluster channel models (2D and 3D IMT- UMi channels) are higher compared to those under single cluster channel.

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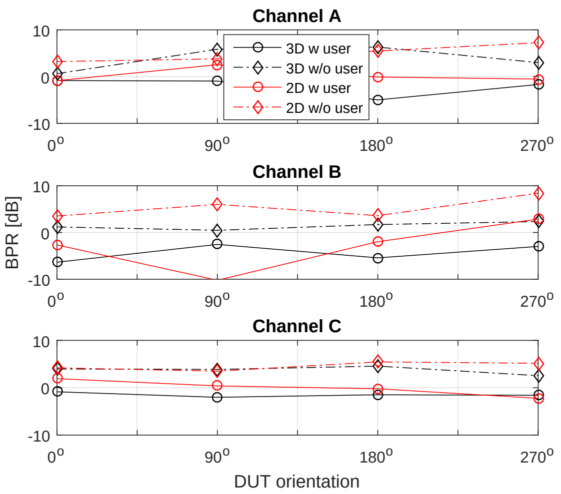

Figure 6. BPR for different channel models in different user modes.

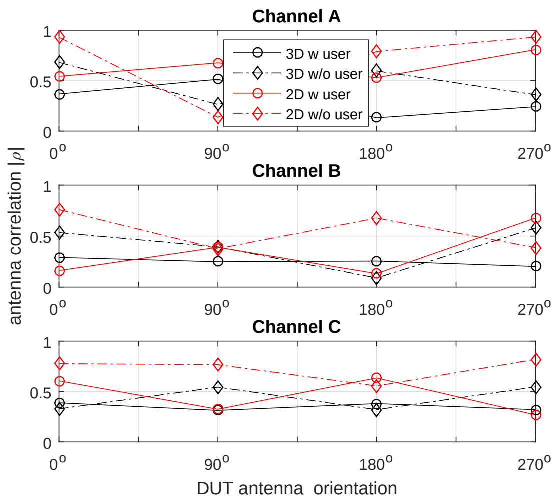

Figure 7. Antenna correlation coefficient for different channel models and rotations in different user modes.

B. Branch power ratio

User effects can greatly affect the BRP values. Figure 6 shows the BPR for different channel models for different orientation angles and operation modes. BPR values vary widely when different channel models or different orientation angles were selected, with a value from 0 dB to 10 dB. In most cases, BPR values are not very sensitive to elevation angles in the channel models. For example, similar BPR values are observed for the 2D and 3D channel models in the channel A and channel C for the free space mode and user influence mode, respectively. However, there are some cases where BPR values are sensitive to elevation angles, e.g. for the channel B. The BRP was very sensitive to DUT orientations, both in free space and user influence modes for all considered channel models, possibly due to their non-isotropic antenna patterns.

C. Antenna correlation

The antenna correlation coefficients for different channel models in different operation modes are shown in Figure 7. Correlation coefficients vary widely when different channel models or different orientation angles were selected, with a value from 0 to 1. This is expected, as correlation values depend directly on the channel spatial profiles and DUT antenna designs. We also notice that correlation coefficients reduce with user influence in most cases, e.g. from 0.93 in the free space to 0.54 with user influence for the 2D vertically polarized spatial cluster channel at orientation angle 0^o. However, in some cases, correlation coefficients increase with user influence, e.g. from 0.26 to 0.51 for the channel A at orientation angle 90^o. This observation is consistent with field measurement results reported in [6], where it reported that the user interaction brought the correlation of two terminals (one with low and one with high correlations) very close to each other. In the MPAC setup, the emulated power angular profile is unaltered, while the DUT antenna patterns might be significantly changed due to presence of user phantom [11]. The antenna correlation depends directly on the channel power angular profiles and complex radiation patterns on the DUT [13]. As a result, the correlation coefficient can be reduced or increased due to introduction of user phantom. Furthermore, correlation coefficients tend to be significantly lower when the elevation spread is enabled, since the red curves tend to be higher than the black curves.

As a summary, a statistical point of view is applied to investigate the user influence, using six spatial channel models, 4 DUT orientations and two operation modes. The BPR and correlation values depend highly on channel spatial profiles, polarization profiles and DUT orientation. The received power per branch can be significantly reduced with the user influence effect. The user influence also significantly impacts BRP and correlation coefficient as well, though the effect can be beneficial or detrimental in terms of MIMO performance. Note that future antenna systems with new capabilities, e.g., with an adaptive radiation pattern, could take advantage of propagation channels and user influence effect.

IV. Conclusion

The main work of this paper is to experimentally evaluate performance of a realistic MIMO mockup together with a realistic user phantom in realistic and controllable multipath propagation scenarios. In an attempt to address this issue, a number of different configurations were tested, such as channel models with different spatial profiles (2D or 3D, single cluster or multi-cluster profile, vertically polarized or dual-polarized), DUT orientations, operation modes (free space and user influence mode). No such work has been reported in the literature, to our best knowledge. Experimental results show that an average received power reduction up to 15 dB was observed with the effect of user influence. The user influence significantly impacts BRP, with a value from 0 dB to 10 dB. In most cases, user influence can reduce the correlation coefficients, though some exceptions exist. The impact of user influence, channel models and antenna designs on system performance metrics, e.g. throughput, capacity, should be investigated in MPAC setups in the future work.

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