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User Influence on MIMO Channel Capacity for Handsets in Data Mode Operation

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***Abstract*—The current paper concerns realistic evaluation of the capacity of the MIMO channel between a BS and handheld device, such as a PDA or smartphone, held in front of the user's body (data mode). The work is based on measurements of the MIMO channel between two widely separated BSs in a micro-cellular setup, and six handsets located in an indoor environment. The measurements are done simultaneously in both the 773.5–778.5 MHz and 2250–2350 MHz bands, and from the two BSs. The handsets are realistic types and were measured both in free space and with twelve different users, using both one and two hands. The random capacities of the channels are evaluated in terms of outage capacity. For an SNR of 10 dB, median capacities in free space of about 4.4–4.7 bit/s/Hz for the low band and about 3.3–3.8 bit/s/Hz for the high band were found. The mean decrease in outage capacity due to the user was found to be up to about 2.2 bit/s/Hz, depending on the band and handset. More results are presented in the paper.**

***Index Terms*—MIMO channels, propagation measurements, channel capacity, user-interaction, dual-band propagation, optical link**

I. Introduction

During the last 10-15 years it has been known that the power transmitted and received from a mobile handset (or cellular phone) may vary significantly. The importance of this has often been reported with differences of several dB's found between handsets [1], and in some cases variations of more than 10 dB were found for different users of the same handset [2]–[5]. The large variations stress the importance of including the user in the design and testing of future handsets, since this has an impact on network performance, battery lifetime, and general user experience.

For a long time handsets have typically been used in *talk mode*, *i.e.*, the situation where the handset is held by the user next to the head for phone usage. A current market evolution is from voice-centric devices into devices where data and applications are equally or more important, such as for smart mobile platforms or smartphones, collectively referred to as "handsets" in the following. With this trend, *data mode* operation becomes more important where the handset is in front of the user and held with one or two hands. The locations of the user's hands and fingers on the handset may be different from those used in talk mode [6]. It is known that the user's hand is the single most important issue when considering the variation in performance in terms of power obtained with different users [7]. Therefore large performance variations may also be expected in data mode operation, since the user's fingers still may interact with the antennas.

Along with the trend towards data mode operation comes a demand for higher data rates. Given the scarcity of radio spectrum, a promising way to achieve higher data rates is to employ multiple-input multiple-output (MIMO) techniques utilizing several antennas on both the transmitter (Tx) and receiver (Rx) side. For example the upcoming long-term evolution (LTE) standard has MIMO capabilities [8].

Today's mobile handsets are densely packed with battery, electronics, and are often equipped with several antennas for different systems. Since small handsets are generally preferred by the users, adding more antennas for MIMO will be difficult and require compromises to be made between the performance and the design and location of the antennas on the handset. The influence of the user's hand on the MIMO performance will be crucial.

It is well known that the performance of a MIMO system is highly dependent on the properties of the radio channel between the Tx and Rx [9], and thus must be included in evaluation. Given that the user interacts with the handset antennas in the near-field, possibly in a dynamic way, it is difficult to include all aspects of both the mobile environment and the user influence without actually including both in a performance measurement. The work in [10] reports on some of the first results on MIMO performance for handheld devices based on propagation measurements with a handset and several live users.

It may be possible to simplify the evaluation, *e.g.*, by using radiation pattern measurements including users, similar to what has been done in the context of single-input single-output (SISO) handset performance evaluation, see [11], [12]. Evaluation of diversity systems, *i.e.*, single-input multiple-output (SIMO), in handsets have also been carried out in this way including phantoms of the user head and hand for talk mode scenarios in [13] and data mode in [14].

Another approach to performance evaluation is presented in [15]. Here a combination of the radiation pattern measurements, including user phantoms, and models of the propagation channel is used, where the model describes all individual plane waves in the channel. Assuming far-field conditions, this method allows a practical separation of antenna measurements and propagation measurements. The work in [15] considers only talk mode. Data mode operation results are given in [16]

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and [17], where a significant user influence on the capacity was found.

For data mode, the work in [18] studies the influence of the user's hand on the capacity, based on simulations of the channel. Based on simulations of both the channel and the radiation patterns, [19] considers the influence of the user's body when the device is carried in a pocket. In the latter two references a significant reduction of (ergodic) capacity was found due to the user.

Other related work includes [20] where the capacity of handsets in data mode is studied with special focus on cross-polarization difference (XPR), based on anechoic room measurements, and [21] where methods for MIMO antenna evaluation are studied, utilizing channel measurements, but focusing on methods rather than practical devices. The early work in [22] studies the performance of different principal antenna types based on propagation measurements, but without user influence. From simulations and measurements in a setup with dipoles in a reverberation chamber, including a simple user phantom and assuming uncorrelated Rx branches, the work in [23] provides a parametric study of how the capacity is influenced by the reduced efficiency and signal blocking, that may be introduced from a nearby user.

Much of the earlier work employs phantoms to mimic the influence of the user, but issues like dynamic behaviour and variations in the MIMO performance among the users are difficult to include with phantoms. Furthermore, results on different types of handsets antennas used in data mode are scarce.

The main topic of the current work is the performance evaluation, in terms of capacity, of different realistic MIMO handsets. Focus is on both achievable capacity as well as the influence of the users of the handsets. The investigations are based on an extensive radio channel measurement campaign in a micro-cellular setup. Simultaneous measurements were carried out from two base stations (BSs) in both 773.5–778.5 MHz and 2250–2350 MHz bands. Six realistic handsets of different types, all equipped with two antennas, are all measured in an indoor environment both in free space and with twelve users in data mode.

The next section describes the measurements in more detail, including the developed handsets equipped with optical units ensuring correct data acquisition. Section III describes the processing of the raw measurement data, while Section IV concerns the obtained results on mean effective gain (MEG), capacity and the user influence. Section V concludes the paper.

II. Measurement Setup

A. Scenario

Successful use of spatial multiplexing modes in a MIMO system requires a rich scattering environment with a wide angular spread of scatterers both near the Tx and the Rx. This generally results in a high rank channel matrix with low correlation among the elements, which in turn results in a high channel capacity [24]. For a cellular network a BS should preferably be near rooftop level or below and not in a highly elevated location that might be preferred from a network coverage point of view. Clearly a sucessful network has to provide a compromise of both high capacity and coverage. In an attempt to create a realistic scenario for the measurements used in the current work, a setup with two BSs was used. BS1 was envisioned to result in high capacity channels, being located some 150 m away from the measurement building with partial line of sight (LOS) and the antennas near rooftop height of surrounding buildings. In contrast, BS2 was located about 500 m away on top of a tall building overlooking the surrounding buildings. An overview of the base stations is given in Table I and Fig. 1–2.

TABLE I
Overview of the two base stations.

	Height above ground [m]	Dist. to MS [m]	No. of Tx Low band	No. of Tx High band
BS1	13	150	2	4
BS2	$\sim$ 60	500	1	0

Fig. 1. View from the antenna location of BS2.

Both indoor and outdoor measurements were made, where the current paper focuses on the indoor part. The measurements took place inside a 3rd floor room with windows towards BS1, where the LOS was partly blocked by buildings. In the room a 4 m by 4 m square was marked on the floor. During the first 5 s of a measurement the user walked from a corner forward along one side of the square to the next corner; the next 5 s the user walked backwards towards the first corner. This was then repeated resulting in a total measurement time of 20 s in which the user kept the same orientation. Four handsets (described below) were measured simultaneously, held by four test users each walking along one of the four sides of the square.

B. Frequency Bands

Two bands were measured simultaneously. An effective sounding bandwidth of about 5 MHz was used at the center frequency of 776 MHz. This band is subsequently referred to as the low band (LB). The high band (HB) was centered at 2300 MHz where an effective sounding bandwidth of about 100 MHz was used. The two bands were chosen to resemble the LTE bands in the 700–800 MHz and 2.3–2.6 GHz ranges, respectively [25]. In practice, both the center frequencies and the bandwidths are compromises given the available equipment and unused frequency spectrum, resulting in the unequal bandwidths.

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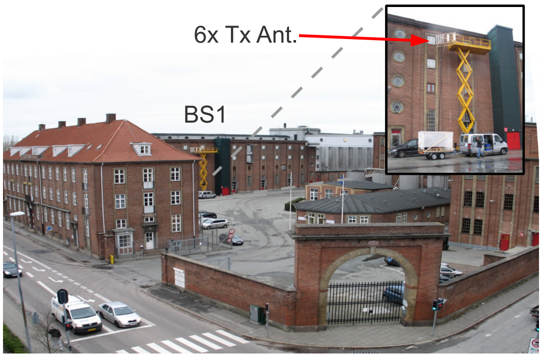

Fig. 2. View towards BS1 from the measurement site.

C. Handsets

The six handsets used in this work are special mock-up handsets which are realistic with respect to the antennas, electromagnetic properties, shape and handling, and at the same time allows for connection to the channel sounding equipment. A straightforward approach would be to connect the antennas in the handsets to the sounder using conventional coaxial cables, but this is an undesirable solution. It is well known that the use of conducting cables on small devices changes the electromagnetic properties, because the cable becomes part of the antenna [26]–[28]. Coaxial cables for measurements need to be low-loss and phase-stable, and are typically of the order 1 cm in diameter, somewhat inflexible and heavy. Attaching such a cable to a small device often makes its handling difficult and hence unnatural, where it is noted that a stiff choke may be needed on the cable, in order minimize the cable influence. In addition, the cable may have to be lead out at an awkward location on the device with respect to easy handling.

An attractive way to avoid the above mentioned problems is to use an optical fiber between the handset and the sounding equipment. By modulating a laser diode with the RF signals received by the antennas it is possible to transfer the signals to the sounder using a flexible plastic fiber. The main difficulty is in designing optical units that are small enough to fit into a typical handset. As described in detail in [29], this has been done for the current work.

The six handsets used in this work all have integrated optical units and all have two antennas, single or dual-band. All the handsets were placed in a plastic casing from PC-ABS material made in a rapid prototyping printer. The material has $\varepsilon_r = 3$, which is comparable to most plastics found in today's phones. The reason for this is to mimic the user handling as closely as possible. The plastic covers provide natural feeling and prevents the user from directly touching the PCB and disturbing the currents and fields in an abnormal way. Finally, grip markings were embedded on the covers for better grip control. An overview of the six handsets is given in Table II. Note that 'H6' is missing from the list. This handset was part of the measurement campaign, but broke during the campaign and therefore the data was discarded. In all cases the handsets are designed for 50 MHz and 100 MHz bandwidth in the LB and HB, respectively.

TABLE II
OVERVIEW OF HANDSETS USED.

Handset	Size [mm]	No	Ant Type	Location	Low band	High band
H1	59 × 111	Rx1	Monopole	Bot-Cnt	✓	✓
PDA style		Rx2	Monopole	Top-Cnt	✓	✓
H2	40 × 200	Rx1	Monopole	Bot-Cnt	✓	✓
Clamshell		Rx2	Monopole	Top-Cnt	✓	✓
H3	40 × 100	Rx1	PIFA	Top-Left	✗	✓
Bar style		Rx2	PIFA	Top-Right	✗	✓
H4	59 × 111	Rx1	Monopole	Top-Left	✗	✓
PDA style		Rx2	Monopole	Top-Cnt	✓	✓
H5	40 × 100	Rx1	Monopole	Top-Left	✓	✗
Bar style		Rx2	Monopole	Top-Right	✓	✗
H7	40 × 100	Rx1	PIFA	Bot	✓	✓
Bar style		Rx2	Monopole	Top	✓	✓

Fig. 3. Handset grips, one hand (OH) for H2 (left) and two hand (TH) for H1 (right).

D. User Grips and Repetitions

Two grips were used, one hand (OH) and two hand (TH). In each case the users placed their fingers in predefined markings on the handsets and held the handset in front of the body at an angle of about 45°. The two grips are shown in Fig. 3.

As mentioned above, variation in performance is expected among the users and therefore more users are involved to allow averaging. Since no *a priori* information exist on the capacity distribution, measurements with twelve users were carried out based on the experience with measurements of MEG [30]. All combinations of the four square sides, two grips and twelve users were measured twice. Firstly with the handsets H1, H2, H3, H4, and secondly with the handsets H1, H5, H6, H7.

In addition all handsets were measured in *free space* where the handsets were mounted at an angle of 45° using Styrofoam on top of a table with wheels. The table was then pushed by a person (bending down) to be measured in the same way as with the users. These measurements were made twice.

E. Sounder Setup

The measurements were carried out using a MIMO channel sounder [31], allowing truly simultaneous measurement of the channels from all seven (three LB and four HB) Tx antennas on the base stations, to the four dual-band Rx antennas. These four Rx antennas are located, one in each, in the four different handsets that are measured at the same time. As described

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above, each handset has two antennas which are connected via a multiplexing switch. Hence, eight dual-band Rx antennas are measured, so that in total a 7×16 MIMO (Tx $\times$ Rx) wide band channel matrix was measured at a rate of 60 Hz to cope with channel changes due to the movements of the users and other changes in the channel.

III. Measurement Statistics

Given the measurements described in the previous section, different MIMO constellations can be studied, *i.e.*, which frequency band and how many Tx and Rx antennas are used. The following are considered in this work,

- BS1,Lo — The two LB Tx antennas from BS1 are used to form a compact 2×2 MIMO setup for each handset.
- BS1,Hi1-2 — Similarly, two of the HB Tx antennas from BS1 are used to form a compact 2×2 MIMO setup.
- BS1,Hi1-4 — All four HB Tx antennas from BS1 are used, resulting in a compact 4×2 MIMO setup.
- BS1+2,Lo — This is a 3×2 distributed MIMO setup where the two Tx antennas from BS1 are used in addition to the single Tx antenna on BS2. Via the normalization described below it is assumed that the Tx power is adjusted so that the average Rx power is the same from BS1 and BS2.

The MIMO channel is described by the matrix $H_i^r(k,m)$ consisting of the elements $h_i^r(k,p,q,m)$ where indices denote the k-th square side, the p-th Tx antenna, q-th Rx antenna, and m-th time index. The MIMO constellations and the choice of handset defines the channels used, and is indicated by the i-index. The scalar $h_i^r(\cdot)$ is the complex gain of the narrow-band channel between the Tx and Rx antennas, obtained via a discrete Fourier transforms of the measured impulse responses (IRs).

To ensure a fair comparison the channels are normalized to the mean power of all handsets in free space. The mean is computed independently for every Tx antenna, mainly to remove path loss differences in the distributed MIMO case and between bands. The free space average power gain for the p-th Tx antenna is computed as

$$\Lambda(p) = \frac{1}{KQMI} \sum_{k=1}^{K} \sum_{q=1}^{Q} \sum_{m=1}^{M} \sum_{i=1}^{I} |h_i^r(k,p,q,m)|^2 \qquad (1)$$

where $K = 4$ is the number of sides of the square, $Q = 2$ is the number of Rx antennas of the handsets, and $M = 1200$ is the number of IR samples along each side. The averaging is done over I handsets. The normalized channel matrix $H_i(k,m)$ has the elements

$$h_i(k,p,q,m) = \frac{h_i^r(k,p,q,m)}{\sqrt{\Lambda(p)}} \qquad (2)$$

Assuming no knowledge at the Tx about the channel state, the instantaneous channel capacity is given by [9]

$$c(k,m) = \sum_{e=1}^{E} \log_2 \left(1 + \frac{\lambda_e \rho}{P}\right) \qquad (3)$$

where the signal to noise ratio (SNR) is ρ, λ_e is the e-th eigenvalue of the matrix $H_i(k,m)H_i(k,m)^H$ and $E = \min(P,Q)$. The number of Tx antennas for the constellation is given by P. The channel capacity $c(k,m)$ is random, and hence a statistical approach is needed. A useful measure is the outage capacity (OC) [32], which is the value χ_α such that the probability $\mathrm{Prb}(c \le \chi_\alpha) = \alpha/100$, where α is the probability level in percent. Thus, the term OC is another name for capacity percentile. This work focus on χ_{10}, χ_{50}, and χ_{90}, *i.e.*, OC at the 10%, 50%, and 90% levels, respectively. The percentiles are found from the empirical cumulative distribution functions (CDFs) by combining all instantaneous capacities from all four square sides, *i.e.*, $c(k,m)$ for all values of k and m.

The capacity results presented in this work are assuming an SNR of 10 dB for the average handset, obtained via the normalization described above. This is equivalent to fixing the Tx power and is aimed at creating a fair comparison among the handsets. For example some handsets may have antennas with higher efficiency than the average and as a result effectively have a higher average SNR.

The issue of normalization and hence SNR is related to the update rate of the power control in the cellular system. The normalization chosen in the current work is based on the average over the complete route (four sides of the square path). Hence both slow and fast fading is preserved and the SNR will vary locally along the route, depending on the handset antennas and the channel. This ensures a fair comparison of the handsets, which would be difficult if, *e.g.*, the slow fading was estimated and removed individually for the handsets, approximating fast power control.

With the aim of understanding capacity results it is useful to study the SISO channels comprising the MIMO channels in terms of MEG. The MEG was originally defined as the ratio of the average power obtained with an antenna under test to the average power obtained with a reference antenna, where the averaging is over measurements carried out in the same realistic environment [33].

Denoting by $a_i(k,p,q,m,n)$ a complex sample of the IR at time-index m, delay-index n, for the p-th Tx antenna, q-th Rx antenna, and measured in the k-th side of the square in the room, the average total power gain is computed as

$$G_i(q) = \frac{1}{KPM} \sum_{k=1}^{K} \sum_{p=1}^{P} \sum_{m=1}^{M} \sum_{n=1}^{N} |a_i(k,p,q,m,n)|^2 \qquad (4)$$

where $N = 2000$ is the number of delay samples, P is the number of Tx antennas for the considered band and base. The meaning of K and M are defined as for (1). The value of $G_i(q)$ may be viewed as the MEG for the q-th antenna of handset/band i, where the reference antenna is a hypothetical antenna collecting all the transmitted power in both polarizations. Note that $G_i(q)$ is computed in (4) using the wideband data since the measurements are calibrated for equal Tx power in the LB and HB, having different bandwidths.

The body loss (BL) $\chi(q)$ for the q-th Rx antenna is defined as the ratio of average total power gains with and without a user [5],

$$\chi(q) = 10 \log_{10} \left[\frac{G(q)^{\text{free}}}{G(q)^{\text{user}}} \right] \qquad (5)$$

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where $G(q)^{\text{free}}$ is the average total power gain in free space conditions, and $G(q)^{\text{user}}$ is the gain when a user is present. The BL not only includes signal power absorbed in the user's body, but also indirect changes in the received power due to the user, such as de-tuning of the antenna and load-pull of power amplifiers in case of uplink transmission. In the following all MEG statistics are based on the logarithms of the mean channel gain $G(q)$.

The presence of a user is expected to result in lower OC compared to the free space case [17], [34]. With the purpose of studying this influence, the term capacity loss (CL) is introduced. In analogy with the BL, the CL is the difference in OC obtained with and without the user when handset is operated in the same environment. More precisely, the CL is defined as

$$\xi_\alpha = \frac{1}{R}\sum_{r=1}^{R} \chi_\alpha^{\text{free}}(r) - \frac{1}{S}\sum_{s=1}^{S} \chi_\alpha^{\text{usr}}(s) \quad (6)$$

where $\chi_\alpha^{\text{usr}}(s)$ is the OC at the α% level, for the s-th user, and $\chi_\alpha^{\text{free}}(r)$ is the similar OC obtained from the r-th measurement in free space conditions.

In order to also quantify the variation of the OC among the users, the capacity variation (CV) is defined as the sample standard deviation

$$\sigma_\alpha = \left[\frac{1}{S-1}\sum_{s=1}^{S}[\chi_\alpha^{\text{usr}}(s) - \bar{\chi}_\alpha^{\text{usr}}]^2\right]^{1/2} \quad (7)$$

where $\bar{\chi}_\alpha^{\text{usr}}$ is the mean OC among the users.

IV. Results

A. Free Space MEG

The MEG for the free space case is shown in Fig. 4, where the handsets are given on the x-axis and all combinations of the two base stations, the two bands, and the two Rx antennas are shown using different lines. First of all it is evident that the gains for the channels originating in BS2 are much smaller than those from BS1. This is due to the longer distance and hence path-loss. Furthermore, for BS1 the HB channel has a higher loss than the corresponding LB channel. Table III lists the path loss averaged over the handsets and Rx antennas, and here the LB to HB difference is found to be 10.4 dB. Using Friis' power transmission equation and assuming, for a moment, free space propagation conditions and identical gains in both the Tx and Rx antennas, the change in frequency alone results in about 9.4 dB power difference. Although these assumptions are dubious it illustrates the importance of the frequency dependence of the channel gain.

The MEG depends on the joint properties of the channel in terms of power distribution versus angle, and the properties of the handset in terms of radiation patterns, including polarization and efficiency. The performance may be analyzed using these terms, see *e.g.* [12], but here it is simply noted from Fig. 4 that there may be several dB's of difference between the two Rx antennas of the same handsets, especially for H1, H2, and H7, as well as among the handsets.

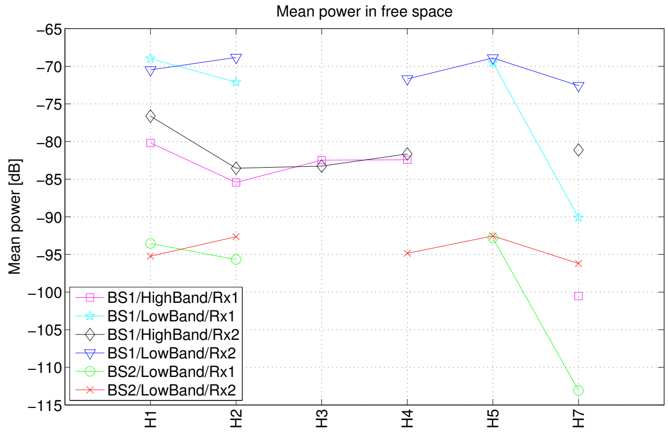

Fig. 4. The MEG in free space conditions. The x-axis indicates the handsets. The different lines in the plot indicates combinations of base, band, and Rx antenna element. The measured points are connected by lines only to ease reading.

TABLE III
PATH LOSS OBTAINED FROM FREE SPACE MEASUREMENTS. AVERAGE OVER ALL HANDSETS AND RX ANTENNAS.

BS1, Low band	BS1, High band	BS2, Low band
74.9 dB	85.3 dB	98.4 dB

B. Body Loss

The mean BLs of all combinations of handset, grip, base, band, and Rx antenna are shown in Fig. 5. From the plot both very high values of about 15 dB are found and also very low found, down to about −1 dB.

The negative BL of about −0.5 dB for H2 is for the Rx2 antenna which is located at the top of the handset, and therefore may be affected only slightly by the users, as evidenced by the generally small BL values for this handset. Although a negative BL is possible theoretically, the observed negative BL may also be the result of a small BL and measurement inaccuracy (see later in Section IV-E). Also for H7, the negative BL is obtained for Rx2 which is located at the top of the handset. The very high 13-15 dB BL found for H7, LB, Rx1 has been identified to be caused by severe de-tuning. This antenna is furthermore located at the bottom of the handset and hence likely to be affected by the users.

1) Top/Bottom Differences: Some of the handsets have both an antenna mounted at the top as well as the bottom of the handset, where the user is much more likely to influence the antenna performance. For these handsets the mean difference in BL for the bottom and the top mounted antenna is about 5.5 dB. For all these handsets the bottom antenna has a higher BL than the top antenna, but the difference is varying from about 0.4 dB for H1, BS1, HB to about 14 dB for H7, BS2, LB.

2) OH/TH Differences: When the TH grip is used the BL is about 1.5 dB larger on average compared to the BL when the OH grip is used. Again, the differences vary depending on the specific combination, but in all cases the TH grip results in the largest BL, ranging from about 0.1 dB for H2, BS2, LB, Rx2, to about 4 dB for H1, BS1, HB, Rx1.

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Fig. 5. The mean of the body loss obtained with 12 different users. The *x*-axis labels are in the form Hn/Grip, where 'Hn' is the handset and 'Grip' is either OH (one-hand) or TH (two-hand). The different lines in the plot indicates combinations of base, band, and Rx antenna element. The measured points are connected by lines only to ease reading.

3) Left/Right Differences: Regarding the handsets where both the antennas are top mounted, the two antennas may also have a difference in the BL. For H3 the right antenna has a BL 4–5 dB larger than the left antenna. For H4 the difference is smaller and less clear, and which antenna has the largest BL depends on the grip. The BL for the left antenna of H5 is about 1.1 dB larger than for the right. Thus, there is no clear tendency and this probably depends on the particular design.

Finally, it is noted that the BL obtained with a given antenna is very similar for BS1 and BS2, as expected.

C. Free Space Capacity

Fig. 6 shows the OCs at the 10%-, 50%-, and 90%-level for free space conditions. The results are computed as described in Section III, using the four different MIMO constellations. It should be noted that H3 does not have LB antennas and H5 does not have HB antennas.

The expression in (3) shows that in general the capacity depends on both the eigenvalues and the SNR. However, it is well known that capacity is strongly dependent on the SNR with a weaker dependence on the eigenvalues [35]. Therefore it is not surprising that the results of Fig. 6 agree well with the MEG shown in Fig. 4.

H4 only has a single antenna in the LB which explains the generally lower capacity of this handset compared to, *e.g.*, H1. Although H7 is a two antenna handset in both the LB and HB the performance in terms of power is rather poor (Fig. 4). In both bands it is essentially a single antenna Rx, resulting in a generally low capacity.

With the above comments on power for the LB, 2×2 MIMO can be formed effectively for H1, H2, and H5. Comparing these handsets, the OCs are found to be fairly similar, with χ_{10}, χ_{50}, and χ_{90} in the ranges (2.7–3.1, 4.4–4.7, 5.9–6.1) bit/s/Hz, respectively.

For the HB, 2×2 MIMO can be formed effectively with H1, H2, H3, H4. Here the OCs are similar for H2-4, (1.9–2.4, 3.3–3.8, 4.7–5.3) bit/s/Hz for the 10%-, 50%, and 90%-levels, respectively, but significantly higher for H1, (3.2, 4.8, 6.8) bit/s/Hz for the three levels. This can be attributed to a higher SNR due to a larger MEG for this handset compared to the rest.

1) LB/HB Differences: Comparing the obtained OCs for the LB and HB no clear tendency is apparent. For H1, the HB has the higher OCs 0.4–1.0 bit/s/Hz, whereas for H2 the LB has higher OCs by 1.2 bit/s/Hz. For H4 the HB OCs are larger by 0.9–1.1 bit/s/Hz, while for H7 they are about the same with differences of -0.3 to 0.2 bit/s/Hz. It should be recalled from Section IV-A that compared to the LB, the HB requires about 10 dB higher Tx power to obtain the same SNR.

2) Extra Tx Antennas, Same BS: Comparing the OCs for the two MIMO constellations BS1,Hi1-2 and BS1,Hi1-4 it is found that the two extra Tx antennas do increase the OC, at least for H1-4. Thus, the extra antennas provide more diversity, although the improvement is marginal. H1 benefits the most, 0.3–0.5 bit/s/Hz, while for H2-4 the OC generally increase by about 0.2 bit/s/Hz.

3) Extra BS: Introducing extra diversity by means of an extra BS may also be beneficial. Comparing the results for the BS1,Lo constellation with those of the BS1+2,Lo constellation reveals that for H2 it is improved 1–1.3 bit/s/Hz for the three OC levels whereas for H1, H4, H5, H7 mainly the χ_{10} values are improved by 0.6–0.9 bit/s/Hz, followed by the χ_{50} values by 0.3–0.6 bit/s/Hz, while the χ_{90} values for H1, H4, and H7 are changed by ±0.1 bit/s/Hz. For H5 χ_{90} is larger by 0.6 bit/s/Hz, but the overall tendency for H1, H4, H5, H7 is that the χ_{10} is improved the most and the main effect of the extra BS is to increase the diversity in the channel.

D. User Influence on Capacity

The CL defined in (6) is shown in Fig. 7 for the handsets measured in the current work. Below these results are analysed from different viewpoints.

1) Handset Differences in CL: Comparing the CL observed for the different handsets, it is immediately apparent that H1 has the *highest* CL, about 2.2 bit/s/Hz in mean over all grips, levels, and constellations. H1 is of the PDA type and has one of the antennas at the bottom where it may be affected by the users, as evidenced by a high body loss (see Fig. 5).

H3 and H5 have *medium* CL of about 1.3 bit/s/Hz in mean, despite being relatively small bar types of handsets. The reason may be that both antennas are located at the top of the handsets, and thus somewhat protected from user influence.

Handsets H2, H4, and H7 have *low* CL. H2 is a relatively long (when open) clamshell type that seems to protect the antennas from the influence of the users, with a CL of about 0.8 bit/s/Hz in mean. Again, Fig. 5 shows that this handset also has a relatively small BL.

H4 is of the PDA type, but unlike H1 with both antennas at the top where the users are unlikely to touch. For H4 the mean CL is about 0.8 bit/s/Hz.

H7 is effectively a single antenna handset, where only the top mounted antenna is receiving significant power. This may explain why this handset in the mean has a CL of only 0.5 bit/s/Hz, the lowest of the handsets.

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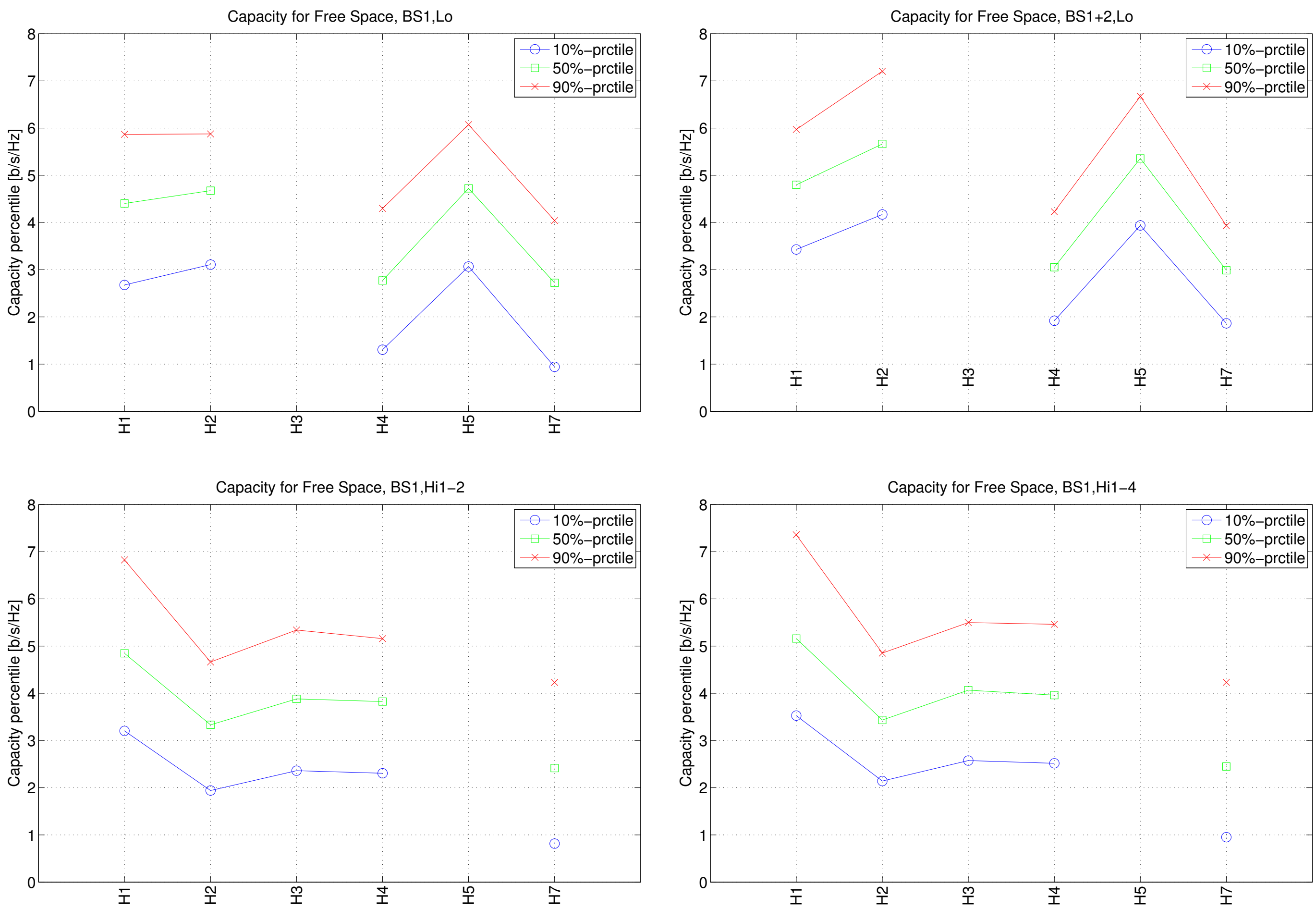

Fig. 6. The outage capacity (OC) for the different handsets in free space conditions. The four plots represent different MIMO constellations. Top-left: BS1, low band. Top-Right: BS1+2, low band. Bottom-left: BS1, high band, Tx1-2. Bottom-Right: BS1, high band, Tx1-4. The measured points are connected by lines only to ease reading.

2) Dependence of CL on Level: Comparing the CL for the different OC levels it appears that sometimes χ_{90} and χ_{50} are changed more than the corresponding χ_{10} mainly for H1 in all constellations, but also, *e.g.*, for H4 and H5 in the LB. Thus, in these cases there is a tendency that high instantaneous capacity values are reduced more than low values.

3) Frequency Dependence of CL: Regarding dependence of the CL on the frequency band, H1, H2, H4, H7 are interesting since they are dual band. Comparing results for BS1,Lo and BS1,Hi1-2, there is a tendency that the CL is higher for the HB than for the LB, in mean by about 0.5 bit/s/Hz.

4) CL for Extra Tx Antennas on the Same Base: Comparing the CLs for BS1,Hi1-2 and BS1,Hi1-4, *i.e.*, when using two or four Tx antennas for the HB, it seen that the CL is generally larger for the BS1,Hi1-4 constellation. The overall mean difference is about 0.16 bit/s/Hz, but for H1 they are generally larger, about 0.3 bit/s/Hz.

The overall increase in OC by adding the two extra Tx antennas is shown in the right half of Table IV, where the CLs due to the users are included. From the table it is clear that the OC improve marginally.

5) CL for Extra Base Station: Similarly, the CLs for the constellations with or without the extra BS is compared, *i.e.*, results for BS1,Lo and BS1+2,Lo. The general tendency is that the CL is larger for the BS1+2,Lo constellations with an overall average of about 0.25 bit/s/Hz. The overall gain by using the extra BS2 transmitter is shown as the left part of Table IV, where it is clear that there is a gain. The question is obviously whether this gain of maximally 0.7 bit/s/Hz justifies the extra cost and difficulties associated with implementing a distributed MIMO system.

TABLE IV
INCREASE IN OUTAGE CAPACITY (OC) OBTAINED BY ADDING MORE TX ANTENNAS, EITHER ON AN EXTRA BASE (BS2), OR ON THE SAME BASE (BS1). SHOWN VERSUS HANDSET AND OC LEVELS AND COMPUTED AS MEAN OVER GRIPS.

	Extra LB BS			Extra HB Tx antennas		
	10%	50%	90%	10%	50%	90%
H1	0.40	0.25	0.05	0.06	0.04	0.08
H2	0.71	0.57	0.55	0.07	0.02	0.04
H3	–	–	–	0.08	0.02	−0.02
H4	0.38	0.07	−0.22	0.07	0.07	0.13
H5	0.72	0.58	0.50	–	–	–
H7	0.42	0.13	−0.15	0.05	-0.02	−0.01

The capacity variation (CV) is defined above in (7) and

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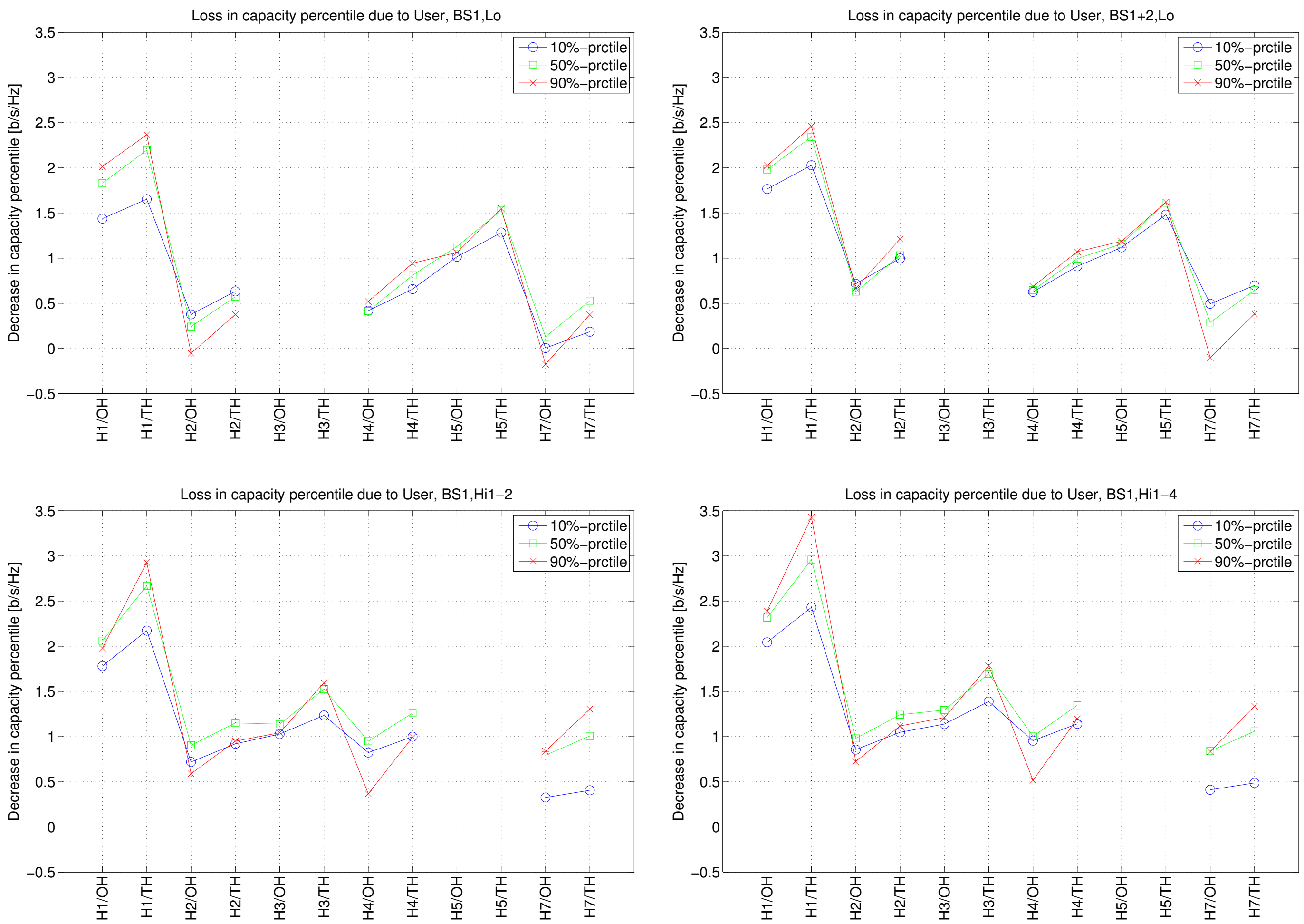

Fig. 7. The mean reduction in the OC when the user is present compared to free space. The x-axis labels are in the form Hn/Grip, where 'Hn' is the handset and 'Grip' is either one hand (OH) or two hand (TH). The four plots represent different MIMO constellations. Top-left: BS1, low band. Top-Right: BS1+2, low band. Bottom-left: BS1, high band, Tx1-2. Bottom-Right: BS1, high band, Tx1-4. The measured points are connected by lines only to ease reading.

Fig. 8 shows the computed values for the different combinations of handsets, probability levels, and MIMO constellations.

6) Dependence of CV on Level: A first observation is that there is a clear tendency that $\sigma_{10} < \sigma_{50} < \sigma_{90}$, *i.e.*, large capacity values are more sensitive to the variations that the users introduce.

7) Handset Differences in CV: On average $\sigma_{10} = 0.3$, $\sigma_{50} = 0.5$, and $\sigma_{90} = 0.6$ bit/s/Hz but there are some variations around these mean values depending on both the handset and band.

On the LB the CV for H2 is in general larger than for H1, perhaps explained by the smaller size of H2 in the part of the clamshell with the user grip. Both H1 and H2 have an antenna at the bottom, and the smaller size could allow for more variation in the grip style. Also H4, with only top antennas, has roughly the same or less variation as does H1.

On the other hand, H2 has significantly less variation on the HB, whereas H1 and H4 have roughly the same variation as on the LB. Thus, although size and location of antennas could explain some of the CV, specific design of the antennas seems to be important too.

Comparing the results for BS1,Lo and BS1,Hi1-2, the CV tend to be a bit lower for the HB than for the LB, about 0.1 bit/s/Hz in the mean. A possible explanation for this is that the whole handset tends to act as antenna for the LB, where for the HB the radiating parts are more confined to the antenna element area. The difference is more pronounced for H2 and H7 than for H1, since the latter has one antenna at the bottom where the user holds and the antennas on H2 and H7 are located where they allow more freedom for variations in the influence of the user.

8) CV for Extra Tx Antennas: The CV values obtained for the two MIMO constellations at the LB, *i.e.*, BS1,Lo and BS1+2,Lo, are roughly the same. Also the CV values for BS1,Hi1-2 and BS1,Hi1-4 are roughly the same.

E. Repeatability

In the preceding sections the performance of the mobile handsets is studied in terms of OC obtained from the measurements. In order to reach conclusions, it is important to address the repeatability of the combined measurement and processing. In principle a repeated measurement with the same user should yield the same OC, but in practice this will not be the case for several reasons, including the following:

- Noise and other errors in the measurement system.

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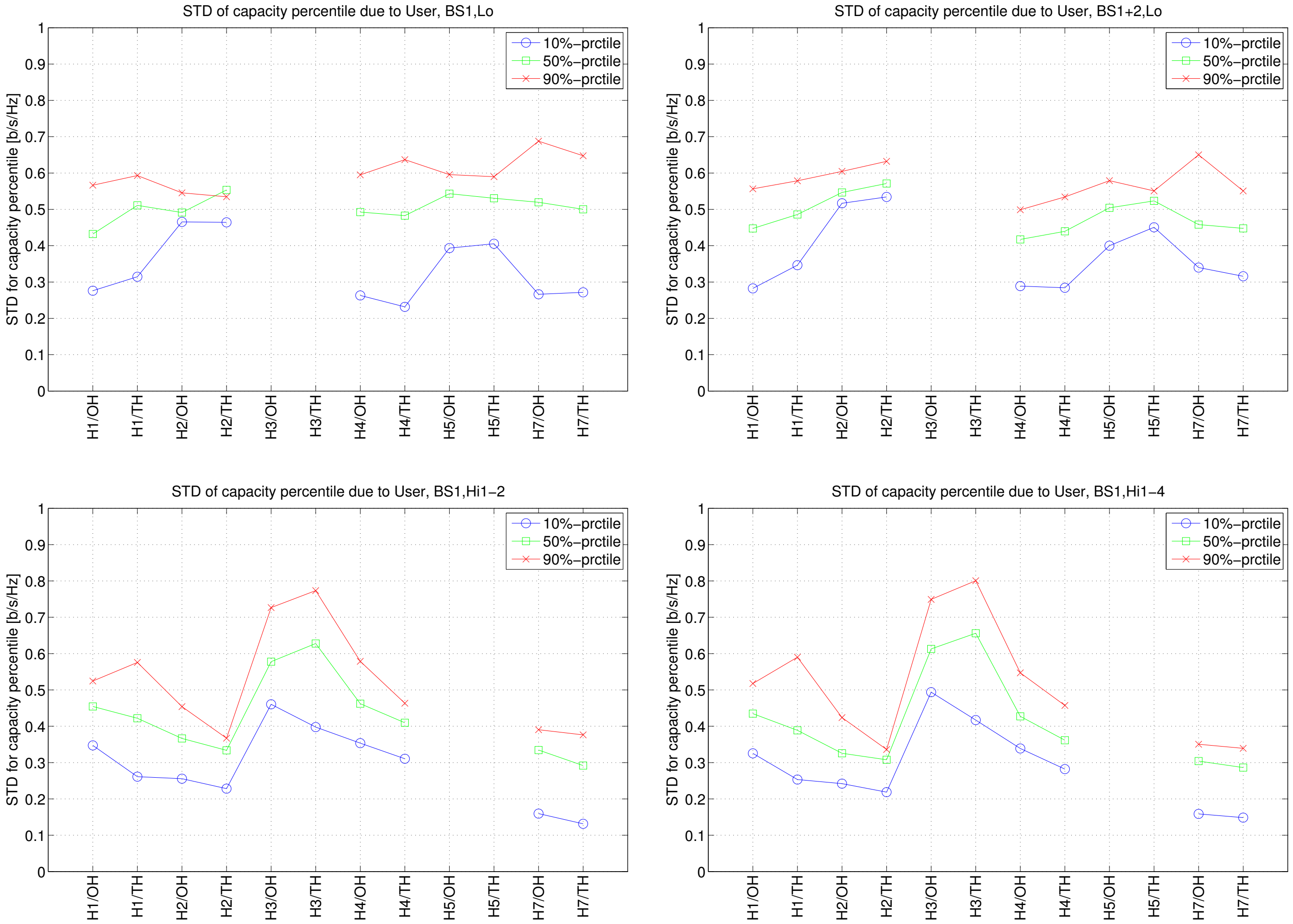

Fig. 8. The STD of the OC when the user is present. The x-axis labels are in the form Hn/Grip, where ‘Hn’ is the handset and ‘Grip’ is either one hand (OH) or two hand (TH). The four plots represent different MIMO constellations. Top-left: BS1, low band. Top-Right: BS1+2, low band. Bottom-left: BS1, high band, Tx1-2. Bottom-Right: BS1, high band, Tx1-4. The measured points are connected by lines only to ease reading.

- Differences in the handling of the handset, such as exact location of the user’s fingers. Even if the user is instructed to use the same grip, small changes are inevitable.
- Similarly, minor changes in, *e.g.*, the user’s route, orientation, and walking speed must be expected.
- Changes in the surrounding environment.

The repeated measurements allow to investigate the repeatability of the derived channel capacity statistics. Every combination of MIMO constellation, user, and grip results in repeated samples of OC. Based on these values (in total 96), percentiles were computed to obtain an overview of the repeatability. Similar to the measurements with users, statistics were computed from the in total 64 combinations in free space. The percentiles regarding accuracy are shown in Table V for both free space and H1. It is noticed that 90% of the observed differences are 0.26 bit/s/Hz or below, and that the deviations tends to increase with the OC level.

Similarly, the repeatability of the measured MEG was studied. Every combination of base, band, Rx antenna, grip, and person resulted in repeated samples of power, in total 144 samples. For the free space case in total 48 combinations are available. Table VI shows the percentiles of the absolute differences for both the free space and user measurements. From the table it is noticed that 90% of the observations are within about ±0.6 dB and ±0.7 dB of the mean value in the free space and user cases, respectively. Furthermore, in all cases the free space percentiles are smaller than those for the user cases, indicating, as expected, that the user introduces extra variability in the measurements. However, the largest part of the variation is due to other sources.

TABLE V
PERCENTILES OF DEVIATIONS FROM MEAN IN REPEATED MEASUREMENTS. THE ROWS OF THE TABLE REPRESENTS THE OUTAGE CAPACITY (OC). THE COLUMNS SHOW THE PERCENTILES OF THE DEVIATIONS FROM THE MEAN OF THE REPEATED OC. THE VALUES ARE IN BIT/S/HZ.

Outage capacity	Repeat. Free, Percentile			Repeat. User, Percentile		
level	10%	50%	90%	10%	50%	90%
10%	0.00	0.06	0.13	0.00	0.05	0.17
50%	0.01	0.05	0.16	0.01	0.06	0.20
90%	0.00	0.04	0.23	0.01	0.07	0.26

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TABLE VI
PERCENTILES OF DEVIATIONS FROM MEAN IN REPEATED MEG MEASUREMENTS. ALL VALUES ARE IN dB.

	Percentile				
	10%	50%	90%	95%	100%
Free space	0.02	0.14	0.56	0.78	1.41
With user	0.03	0.23	0.73	0.95	1.55

V. CONCLUSION

The user influence on the channel power gain was investigated in terms of the body loss (BL). Similar to previous findings for talk mode, the BL in data mode was found to depend highly on the design of the handset and the usage, with approximate mean values ranging from 0 dB to 10 dB.

In free space the outage capacity (OC) is generally similar for the handsets, but a high MEG also results in a higher OC, as this effectively gives a higher SNR. Measured values of the 50% OC were 3.3–4.7 bit/s/Hz for an SNR of 10 dB, depending on handset and frequency band. The path loss is about 10 dB higher on the high band (HB) than on the low band (LB).

As expected, the OC is reduced the most when users are likely to touch areas near the antennas. A reduction of up to about 2.2 bit/s/Hz was found for a handset with an antenna at the bottom, compared to about 0.8 bit/s/Hz for a relatively large handset with top mounted antennas. In mean the OC reduction is 0.5 bit/s/Hz higher on the HB than on the LB.

Using more Tx antennas on the base than on the mobile may in free space introduce extra diversity, increasing the 10% OC about 0.2 bit/s/Hz, but when users are introduced the increase is only marginal. Using an extra BS (distributed MIMO) can provide some extra diversity in the free space case, with a 10% OC increase of up to about 0.9 bit/s/Hz, which is reduced to a maximum of about 0.7 bit/s/Hz when the user is present. Note that these numbers are for the best case with no path loss differences between the BSs.

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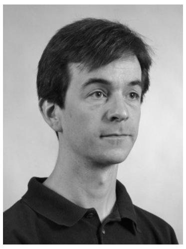

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