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*Published in:*
Antennas and Propagation (EUCAP), 2012 6th European Conference on

*DOI (link to publication from Publisher):*
10.1109/EuCAP.2012.6206085

*Publication date:*
2012

*Document Version*
Accepted author manuscript, peer reviewed version

# User Influence on the Mean Effective Gain for Data Mode Operation of Mobile Handsets

J. Ø. Nielsen[*], B. Yanakiev[*‡], I. B. Bonev[*], M. Christensen[‡], G. F. Pedersen[*], C. Luxey[§], A. Diallo[§], I. Dioum[¶]

[*]APNet, Department of Electronic Systems, Faculty of Engineering and Science, Aalborg University, Denmark
[‡]Molex, Antenna Business Unit, Aalborg, Denmark
[§]LEAT-CNRS, University of Nice-Sophia Antipolis, France
[¶]Département Génie Informatique, Ecole Supérieure Polytechnique, Université Cheikh Anta Diop de Dakar, Sénégal

***Abstract*—The current paper presents statistics on the mean effective gain (MEG) for mobile handsets. The results are based on a large measurement campaign in an urban environment where the propagation channel from two different base stations to seven different handsets were measured in two bands (776 MHz and 2300 MHz). The handsets were of different types (bar, clamshell, smartphone), all had two antennas and were used in data (browsing) mode. All handsets were measured with twelve different users with both one-hand and two-hand grips. The body loss, the mean difference between the MEG in free space and with a user, was found to be up to about 15 dB with typical values below 6 dB. Further results are given in terms of mean values, standard deviations, and analyses for differences due to antenna location and user grip style. Finally, the body loss distribution is modeled and used for estimation of confidence intervals.**

***Index Terms*—MIMO channels, MEG, mean effective gain, propagation measurements, user-interaction, body loss, dual-band propagation, optical link**

## I. Introduction

In a cellular network the radio channel is important since it in many ways influences both the user experience as well as the network costs. In the current work focus is on the performance of a mobile handset in terms of the power received and transmitted, because this may impact the data throughput, coverage, battery lifetime, and the interference level in the network.

In order to obtain a realistic performance estimation it is important to consider the multipath propagation channel. A useful measure is the mean effective gain (MEG), defined as the mean power received by the handset to the mean power received by a reference antenna, where the mean values are computed for a realistic route in a mobile environment [1].

The fundamental radio propagation cannot be changed but the antennas and the handling of the handsets can be optimized. The importance of this has often been reported with differences of several dB's found between handsets [2], and in some cases more than 10 dB variations found for different users of the same handset [3]–[5]. With the trend towards data oriented use of the mobile handsets, *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 obtained with different users. Therefore large performance variations may also be expected in data mode operation, since the user's fingers still may interact with the antennas. Currently, there are few studies of the performance of handsets used in data mode [7], [8] where the MEG is computed via assumed models of the environment and based on measured radiation patterns including hand phantoms. While these works are useful for studying the involved mechanisms, it is important to also have direct measurements involving real users and handset prototypes. In general the user interacts with the near-fields of the antennas and therefore must be included in the evaluation, but it is very difficult to produce hand phantoms which interacts with the handset in a realistic way.

The current paper presents statistics on the MEG based on dual-band MIMO channel measurements involving twelve different users and seven realistic handset prototypes. The channels from two widely separated base stations to an indoor environment are measured simultaneously in both bands. Although MEG is a metric relevant for single-input single-output (SISO) channels, the MEG results are also relevant for multiple-input multiple-output (MIMO) systems. It was previously concluded that a main determining factor for MIMO capacity is the ability of the antennas to transfer power over a given propagation channel [9], [10]. In other words, the gains of the individual links are important, as are any losses in the antennas including the effects of the user.

## II. Measurements

The measurements were carried out in a realistic scenario with two bases, one (BS2) providing an 'umbrella' cell and another (BS1) acting as a close by, high capacity cell. BS1 was located some 150 m from the measurement building with partial line of sight (LOS), while BS2 was located about 500 m away on top of a tall building overlooking the surrounding buildings. An overview of the bases is given in Table I and Fig. 1.

J. Ø. Nielsen and B. Yanakiev are supported by the Danish National Advanced Technology Foundation via the Converged Advanced Mobile Media Platforms (CAMMP) project. The results and conclusions presented by the authors in this article are not necessarily supported by the other partners of the CAMMP project.


Presented at the *6th European Conference on Antennas and Propagation (EuCAP 2012)*, p. 2759–2763. DOI: 10.1109/EuCAP.2012.6206085.


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

TABLE I
OVERVIEW OF THE TWO BASE STATIONS.

| | Height above ground [m] | Distance [m] | No. of Tx 776 MHz | No. of Tx 2300 MHz |
|---|---|---|---|---|
| BS1 | 13 | 150 | 2 | 4 |
| BS2 | $\sim 60$ | 500 | 1 | 0 |

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 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 were measured simultaneously, held by four test users each walking along one of the four sides of the square.

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. 2. All combinations of the four 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

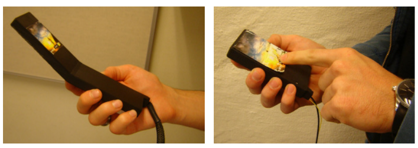

Fig. 2. One-hand (OH) grip for H2 (left) and two-hand (TH) for H1 (right)

TABLE II
OVERVIEW OF HANDSETS USED.

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

a person (bending down) to be measured in the same way as with the users.

The measurements were carried out using a multiple-input multiple-output (MIMO) channel sounder, allowing truly simultaneous measurement of all seven (three LB and four HB) Tx channels and four dual-band Rx branches. As each handset has two antennas, a switch is used for multiplexing. The complete $7 \times 16$ MIMO wideband channel matrix was measured at a rate of 60 Hz to cope with channel changes due to the movements of the users and otherwise.

The seven 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. Optical fiber links were used for this in order to preserve the electromagnetic properties of the handsets. Implementation details of the optical links are available in [11].

The seven handsets all have two antennas, single or dual-band, and have 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 are embedded on the covers for better grip control. An overview of the seven handsets is given in Table II. Note that H6 broke during the measurement campaign, and hence has been omitted.

## III. Data Processing

The measurements described in Section II results in complex impulse response (IR) measurements of the complete


Presented at the *6th European Conference on Antennas and Propagation (EuCAP 2012)*, p. 2759–2763. DOI: 10.1109/EuCAP.2012.6206085.

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

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

where $K = 4$ is the number of sides of the square, $M = 1200$ is the number of IR samples along each side, $N = 2000$ is the number of delay samples, $P$ is the number of Tx elements for the considered band and base. The value of $G(q)$ may be viewed as the MEG, where the reference antenna is a hypothetical antenna collecting all the transmitted power in both polarizations.

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

$$\chi(q) = 10\log_{10}\left[\frac{G(q)^{\text{free}}}{G(q)^{\text{user}}}\right] \qquad (2)$$

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 statistics are based on the logarithms of the mean channel gain $G(q)$.

## IV. Repeatability

In principle a repeated measurement with the same user should yield the same MEG, but in practice this will not be the case for several reasons, including the following:

- Noise and other uncertainties in the measurement system.
- 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.

As described in Section II all measurements with H1 were performed twice. For every 4 users, all measurements with the first set of handsets {H1, H2, H3, H4} were carried out, followed by a similar sequence of measurements with the second set {H1, H5, H6, H7}. Therefore, the repeated measurements with H1 were separated in time and can to some extend be considered independent, since other measurements were made in between.

The repeated measurements allow to investigate the repeatability of the measured channel gain. Every combination of base, band, Rx element, grip, and person results in repeated samples of power, in total 144 samples. For every combination the absolute difference between the samples and the mean over the repeated values is computed. Based on these values percentiles were computed to obtain an overview of the repeatability. For free space, all measurements were performed twice for all handsets (and four times for H1). Similar to the measurements with users, statistics were computed from the total 48 combinations. Table III 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 III
Percentiles of deviations from mean in repeated 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 |

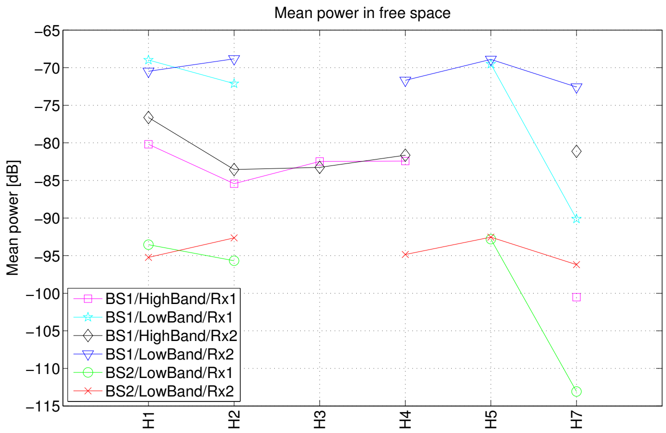


Fig. 3. The mean channel gain in free space conditions. The x-axis indicates the handsets. The different lines in the plot indicates combinations of base, band, and Rx antenna element. The measured points are connected by lines only to ease reading.

## V. Free Space MEG

The mean link gain is shown in Fig. 3, where the handsets are given on the x-axis and all combinations of the two bases, 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 much longer distance and hence path-loss. Furthermore it is clear, that for BS1 the HB channel has a much higher loss than the corresponding LB channel, about 10.4 dB averaged over handsets and Rx channels.

From Fig. 3 it is also interesting to note that there may be several dB's difference between the two Rx channels of the same handsets, especially for H1, H2, and H7.


Presented at the *6th European Conference on Antennas and Propagation (EuCAP 2012)*, p. 2759–2763. DOI: 10.1109/EuCAP.2012.6206085.

## VI. Body Loss

### A. Mean

The mean BL'es of all combinations of handset, grip, base, band, and Rx channel are shown in Fig. 4. 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. 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.

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.

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.

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 antenna.

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

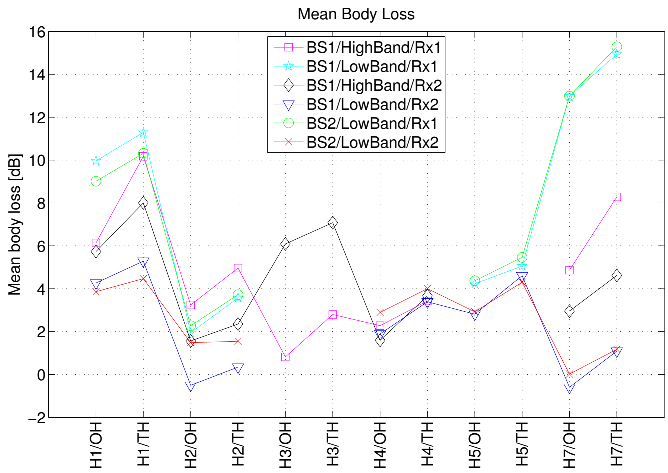


Fig. 4. The mean of the body loss obtained with 12 different users. The x-axis labels are in the form Hn/Grip, where 'Hn' is the handset and 'Grip' is either OH (one-hand) or TH (two-hand). The different lines in the plot indicates combinations of base, band, and Rx antenna element. The measured points are connected by lines only to ease reading.

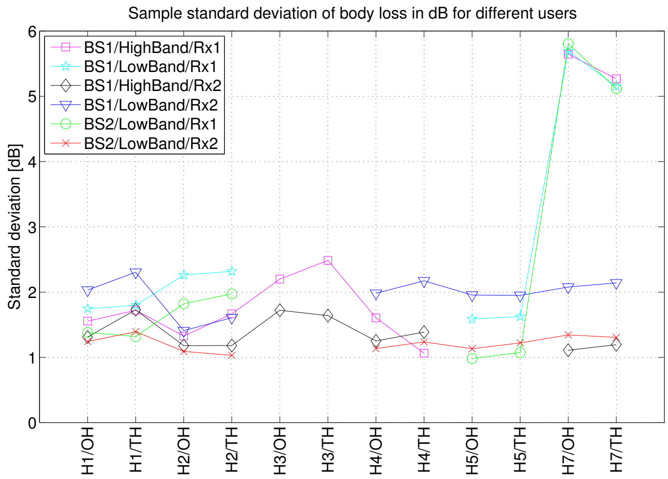


Fig. 5. The sample standard deviation of the body loss obtained with 12 different users. The x-axis labels are in the form Hn/Grip, where 'Hn' is the handset and 'Grip' is either OH (one-hand) or TH (two-hand). The different lines in the plot indicates combinations of base, band, and Rx antenna element.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

### B. Standard Deviation

The standard deviation (STD) of the BL observed with the individual users is shown in Fig. 5. Most values are in a range of about 1–2.5 dB, but for H7 all the values for the Rx1 antenna are 5–6 dB. This particular antenna is located at the bottom and hence is in the area where the users typically interact with the phone. As mentioned above, the same antenna also has a high mean BL due to de-tuning which also is likely to make it sensitive to the type of user interaction.

Judging by the mean over base, band, and Rx antenna for H1, H2, H3, H5 the STD tends to be larger for the TH grip than for the OH grip by about 0.05–0.17 dB. It is the opposite for H4, H7, where STD for the OH grip is larger by about 0.03–0.25 dB.

For the handsets with both bottom and top mounted antennas, *i.e.*, H1, H2, H7, it is mainly H2 and H7 clearly showing the tendency that the bottom antenna has larger STD than the top antenna. For H1 the differences are smaller. A possible explanation for this could be that the larger size of H1 generally leads to a more common grip than the smaller H2 and H7.

For handsets with only antennas at the top, *i.e.*, H3, H4, H5, the differences are generally less than 0.5 dB. Only H3 for TH grip the STD difference for the left and right antenna is about 0.8 dB. The generally lower STD may be explained by the less likely user interaction with the top mounted antennas.


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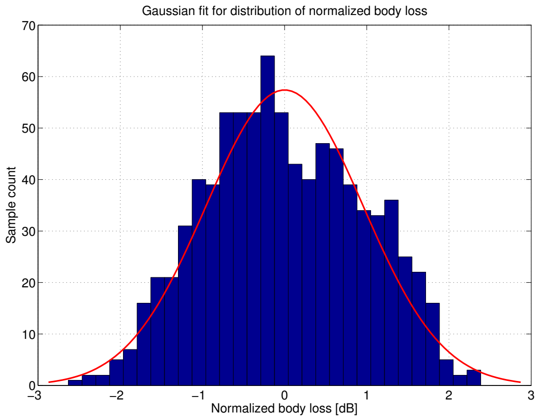


Fig. 6. Histogram and Gaussian fit of the observed body loss with twelve test users of seven handsets in two frequency bands and with two bases. Before computing the histogram the data was normalized with the mean and standard deviation, see Fig. 4 and Fig. 5.

### *C. Body Loss Distribution*

Since the estimated BL values are random values, they should be accompanied with confidence intervals (CI's) [12]. For the computation of CI's the distribution of the BL must be known, and it is therefore estimated from the observed data. Ideally, the BL distribution should be estimated for every combination of base, band, handset, and Rx antenna. However, estimation of the distribution using the directly available measurements for 12 persons is not useful, since the number of samples is too low. Instead, the following assume all combinations result in samples from the same distribution, possibly with different parameters. By normalization with the mean and STD values discussed in the preceding sections all samples may be used to estimate the distribution.

Fig. 6 shows a histogram of all the normalized samples, including the PDF of a Gaussian fit. Although not a perfect fit, the Gaussian model seems to be reasonable. It is important to realize that the Gaussian model includes both variations due to the users, such as slightly different grips or size of hands, as well as changes in the environment, and measurement errors.

If it is assumed that the Gaussian model also holds for the individual combinations of handset, band, *etc.*, it is possible to define CI's for the mean BL. The CI has the form $[\bar{x}-\beta, \bar{x}+\beta]$ with $\bar{x}$ the sample mean and

$$\beta = \frac{s t_{N-1,\alpha/2}}{\sqrt{N}} \tag{3}$$

where $s$ is the sample standard deviation, and $t_{n,\alpha/2}$ is the Student's $t$-distribution with $n$ degrees of freedom at a $100\alpha$ percentage level [13]. As an example, $\beta \simeq 0.52$ for $\alpha = 0.1$ and $N = 12$, meaning that with 90% probability the true mean is within an interval of $\pm 0.52 \cdot s$ around the sample mean value.

## VII. Conclusion

The MEG obtained with the different handset antennas in free space show differences of several dB's and in some cases up to about 8 dB.

The mean BL was in the range of about 0–15 dB, with the majority of values below 6 dB. For handsets with antennas both at the top and the bottom, a mean difference in the BL for the two antennas was found to be about 5.5 dB. Although large variations exist, the user's hand is more likely to cover the bottom antenna, hence the larger mean BL. Using two hands instead of one always increases the BL, on average about 1.5 dB. As expected, the mean BL obtained with the two different base stations are about the same.

The STD of the BL obtained with different users was also analyzed. Most of the STD values were 1–2.5 dB, with exceptions up to 5–6 dB. No clear tendency was found regarding the influence of the one/two hand grip on the STD, and only small differences were found between top/bottom antenna location and between left/right side location.

Finally, it was found that the BL variation among the users approximately follows a Gaussian distribution, allowing easy estimation of confidence intervals for the mean BL.

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