Channel Statistics for MIMO Handsets in Data Mode

Nielsen, Jesper Ødum; Yanakiev, Boyan; Barrio, Samantha Caporal Del; Pedersen, Gert Frølund

Published in:
Antennas and Propagation (EuCAP), 2014 8th European Conference on

DOI (link to publication from Publisher):
10.1109/EuCAP.2014.6902413

Publication date:
2014

Document Version
Accepted author manuscript, peer reviewed version

Channel Statistics for MIMO Handsets in Data Mode

Jesper Ødum Nielsen[1], Boyan Yanakiev[1,2], Samantha Caporal Del Barrio[1], Gert Frølund Pedersen[1]

[1]APNet, Dept. of Electronic Systems, Faculty of Engineering and Science, Aalborg University, Denmark
[2]Intel Mobile Communications, Denmark

***Abstract*—The presented work is based on a large dual-band, dual-base outdoor-to-indoor multiple-input multiple-output (MIMO) channel measurement campaign, involving ten different realistic MIMO handsets, held in data mode by eight test users. Various different use cases (UCs) are measured. Statistics on the channel capacity, mean effective gain (MEG), branch power ratio (BPR), and correlation coefficients between Rx, Tx, and cross-link channels are presented.**

I. Introduction

MIMO technology is an important part of the relatively recent long-term evolution (LTE) cellular system standard, where typical devices may be handheld. It is known that the capacity of MIMO systems is highly dependent on the channel properties, such as the mean power and correlation between the individual MIMO sub-channels [1]. Due to, *e.g.*, absorption and blocking of signal power, it is expected that a user holding the device may have a significant influence on the device performance and capacity of the MIMO channel. The user influence was previously demonstrated for single-input single-output (SISO) systems [2] and also for MIMO systems [3]–[5], but few works exist with statistics on the channel properties for realistic devices of modern type and including the presence of real users.

The current work is based on a large measurement campaign and presents statistics for the realistically obtainable capacity and the channel parameters MEG, BPR and channel correlation coefficients (CCs). The measurement campaign used two dual-band MIMO base stations (BSs) and involved eight test users, handling ten different handsets in various ways in front of the body, as for data mode use. The mockup handsets are of different types and made in realistic plastic casings using a 3D-printer, and further utilizing optical feeding to avoid conductive cable effects [6]. In total about 3,000 different combinations of handsets, orientations, users, and UCs are included.

II. Channel Measurements

All measurements were carried out in a setup with two BSs and mobile users located inside a four story office building

J. Ø. Nielsen and B. Yanakiev were 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.

Fig. 1. Left: View from BS2 towards measurement location. Right: Users during measurements, with the user squares and orientations A–D indicated.

located in the city center of Aalborg, Denmark. One BS (BS1) was located about 150 m away from the building and was elevated about 21 m above the ground, using a lift. A second BS (BS2) was located about 500 m away on top of an about 60 m tall building overlooking the surroundings of mostly 2-3 story buildings, see Fig. 1.

The measurements were carried out using a wideband MIMO channel sounder [7], connected to four different handsets, which are measured simultaneously. Each handset has two dual-band antennas, so that four receiver (Rx) channels must be measured for each handset. Each of the two BSs have two dual-element arrays, one for each band. Thus, in total a 8×16 MIMO (Tx $\times$ Rx) wide band channel matrix was measured.

The measurement of a single sample of the full MIMO channel lasts about 164 μs and is repeated at a rate of 60 Hz, resulting in Nyquist sampling of the channel for relative movements of the users and other objects at speeds up to about 3.9 m/s. The channel impulse responses (CIRs) were obtained with a sampling rate of 400 MHz, corresponding to a 2.5 ns sampling in delay. Each measurement run, described below, lasts 20 s, corresponding to 1200 MIMO CIR samples.

The two measured frequency bands were centered about 796 MHz and 2300 MHz, with effective bandwidths of about 5 MHz and 30 MHz, respectively. The bands are labeled, respectively, as low band (LB) and high band (HB) in the following. The two antenna branches of the arrays on the BSs were separated by about 5 wavelengths, for both the LB and HB.

Table I lists the handsets used, which were all connected to the sounder via optical fibers to avoid conductive cable effects [6]. More information about the handsets can be

Presented at *The 8th European Conference on Antennas and Propagation (EuCAP 2014), April 2014. DOI: 10.1109/EuCAP.2014.6902413.*

found in [8]. The handsets are measured simultaneously in groups of four, with H6 always present, in order to have a reference. Different UCs are considered and in order to include the variation in the influence by the user's hand and body, measurements with different persons were performed. For the $G1 = \{H6, H1, H2, H5\}$ set of handsets eight persons were measured for all UCs, while four persons where measured with the $G2 = \{H6, H3, H4, H11\}$ and $G3 = \{H6, H12, H13, H14\}$ sets. Note, H6r is identical to H6 but used upside down.

The UCs are all in *data mode* where the users hold the handset in front of the body, as when viewing the screen and using one or two hands. The UCs were: landscape mode for left hand only (LRHL), right hand only (LRHR), and two hands (LRTH), and in portrait mode with right hand only (PHR) and two hands (PTH). In addition, corresponding free space (FS) measurements were made with the handsets mounted on expanded polystyrene (EPS) at an angle of 45°.

For all the measurements, the mobile stations were inside a large hallway/common room on the 3rd floor of a building mainly made of concrete, representing a typical indoor environment. The room only has windows in the ceiling with no line of sight (LOS) to the BSs. The adjacent rooms have regular windows, also with no LOS to the BSs. All measurements were made inside or around four squares marked on the floor with about 1 m side length. The squares were arranged in a cross, centered in the room with size about 7 × 12 m. The squares are labeled A, B, C, D, as illustrated in Fig. 1. During each measurement run the user and handset moved randomly inside all of the square, but kept the same posture and orientation with respect to the environment. Each square A–D represents different orientations, separated by 90°.

In total about 3,000 different combinations of handsets, orientations, users, UCs are included, of which about 1,000 are measured in landscape mode with a user, about 900 are in portrait mode with a user, and about 1,100 are in FS.

III. Data Processing

In the following different constellations are considered,

- BS1LB The two LB transmitter (Tx) branches from BS1 are used to form a 2 × 2 MIMO setup for each handset.
- BS1HB Similarly, the two HB Tx branches from BS1 are used to form a 2 × 2 MIMO setup.
- BS2LB The two LB Tx branches from BS2 are used to form a 2 × 2 MIMO setup for each handset.
- BS2HB Similarly, the two HB Tx branches from BS2 are used to form a 2 × 2 MIMO setup.

The MIMO channel is described by the matrix $H_i^r(m)$ consisting of the elements $h_i^r(p, q, m)$ where indices denote, respectively, the p-th Rx antenna branch, the q-th Tx antenna branch, and the m-th time index. The i-index specifies a combination of the MIMO constellation, handset, orientation/location, repetition number, user, and UC, where each combination results in a different MIMO channel measurement. For brevity, the combination details are omitted in the following description. The scalar $h_i^r(p, q, m)$ is the complex gain of the narrow-band channel between the Tx and Rx branches, obtained via discrete Fourier transforms of the measured complex CIRs.

TABLE I
Overview of the handsets used in the measurement campaign.

Handset	Elec. size [mm]	No	Ant Type	Location	Low band	High band
H1 PDA	59 × 111	Rx1 Rx2	ILA ILA	Bot Top	✓ ✓	✓ ✓
H2 PDA	59 × 111	Rx1 Rx2	Mono Mono	Top-Side/R Bot-Side/R	✓ ✓	✓ ✓
H3 PDA	59 × 111	Rx1 Rx2	Mono Mono	Top-Side/R Bot-Side/R	✓ ✗	✓ ✓
H4 PDA	59 × 111	Rx1 Rx2	ILA Mono	Top Top-Side/R	✗ ✓	✓ ✓
H5 PDA	59 × 111	Rx1 Rx2	Mono Mono	Top-Side/L Top-Side/R	✓ ✓	✓ ✓
H6 PDA	59 × 111	Rx1 Rx2	ILA Mono	Top Side/L	✓ ✓	✓ ✓
H6r PDA	59 × 111	Rx1 Rx2	ILA Mono	Bot Side/R	✓ ✓	✓ ✓
H11 PDA	59 × 111	Rx1 Rx2	PIFA PIFA	Top Bot	✓ ✓	✓ ✓
H12 Bar	40 × 100	Rx1 Rx2	PIFA PIFA	Top Bot	✓ ✓	✓ ✓
H13 PDA	59 × 111	Rx1 Rx2	Helix Helix	Top/L Bot/L	✓ ✓	✗ ✗
H14 Bar	40 × 100	Rx1 Rx2	Mono Mono	Top/L Top/R	✓ ✓	✗ ✗

To ensure a fair comparison, the channels are normalized to the mean power of all handsets in FS. The mean is computed independently for every Tx branch, mainly to remove path loss differences due to the distance and frequency. The FS average power gain for the q-th Tx branch is computed as

$$\Lambda(q) = \frac{1}{PMI} \sum_{p=1}^{P} \sum_{m=1}^{M} \sum_{i=1}^{I} |h_i^r(p, q, m)|^2 \quad (1)$$

where $P = 2$ is the number of Rx branches of the handsets, and $M = 1200$ is the number of samples in each measurement. The averaging is done over I combinations of handset, orientation, UC, *etc.* In the following $H_i(m)$ denotes the normalized channel matrix.

With the normalized narrow band channel, the signal received by a handset can be described as $y = Hs + n$, where s is the vector of transmitted symbols with length Q, n is a same size noise vector, and H is the $P \times Q$ random channel matrix. Assuming that the transmitter has no knowledge of the channel, the capacity of the channel is given by [9]

$$c_i(m) = \sum_{e=1}^{E} \log_2 \left(1 + \frac{\lambda_i(e, m)\rho}{Q} \right) \quad (2)$$

where ρ is the signal to noise ratio (SNR), $\lambda_i(e, m)$ is the e-th eigenvalue of the matrix $H_i(m)H_i(m)^H$ and $E = \min(P, Q)$.

Presented at *The 8th European Conference on Antennas and Propagation (EuCAP 2014), April 2014. DOI: 10.1109/EuCAP.2014.6902413.*

The number of Tx antennas for the constellation is given by Q. The instantaneous channel capacity $c_i(m)$ is random and thus statistics are used for characterization. For every individual measurement the outage capacity (OC) is computed, which is the value χ_i^α such that the probability $\text{Prb}(c \leq \chi_i^\alpha) = \alpha/100$, where α is the probability level in percent. The OC is computed for each individual measurement, denoted by i, consisting of $M = 1200$ instantaneous MIMO channel samples.

The mean effective gain (MEG) and the branch power ratio (BPR) are defined as follows,

$$\text{MEG: } \alpha_i = \frac{1}{PQ}\sum_{p=1}^{P}\sum_{q=1}^{Q}\gamma_i(p,q) \quad (3)$$

$$\text{BPR: } \beta_i = \frac{1}{Q}\sum_{q=1}^{Q}\frac{\gamma_i(2,q)}{\gamma_i(1,q)} \quad (4)$$

$$\gamma_i(p,q) = \frac{1}{M}\sum_{m=1}^{M}|h_i(p,q,m)|^2 \quad (5)$$

The correlation properties of the channel are analyzed using the estimated CC matrix, for the 2×2 MIMO case given by

$$\begin{bmatrix} c_{11,11} & c_{11,21} & c_{11,12} & c_{11,22} \\ c_{21,11} & c_{21,21} & c_{21,12} & c_{21,22} \\ c_{12,11} & c_{12,21} & c_{12,12} & c_{12,22} \\ c_{22,11} & c_{22,21} & c_{22,12} & c_{22,22} \end{bmatrix} = \begin{bmatrix} 1 & r_1 & t_1 & s_1 \\ r_1^* & 1 & s_2 & t_2 \\ t_1^* & s_2^* & 1 & r_2 \\ s_1^* & t_2^* & r_2^* & 1 \end{bmatrix}$$

where $c_{pq,p'q'}$ is the estimated CC between $\bar{h}_i(p,q,m)$ and $\bar{h}_i(p',q',m)$, obtained using the M narrow band samples and where $\bar{h}_i(\cdot)$ is the demeaned and normalized version of $h_i(\cdot)$. Note that a CC matrix is obtained for each individual channel configuration $H_i(\cdot)$. In the following, the Tx-correlation coefficient (TxCC) is the absolute mean of t_1 and t_2, the Rx-correlation coefficient (RxCC) is the absolute mean of r_1 and r_2, and cross-link correlation coefficient (LxCC) is the absolute mean of s_1 and s_2.

IV. Results

For a given combination of handset and MIMO constellation, the MEG depends on the UC, orientation, and the user, if present. In the following the MEG is considered random, and the individual measurements obtained with different combinations of user orientations, UC, different users, and FS result in samples of the MEG, depending on the combination of handset and constellation. The samples are analyzed using statistics, specifically median values and boxplots.

Similarly, statistics of the BPRs, TxCCs, RxCCs, LxCCs, and OC are obtained as described in the sections below.

A. Mean Effective Gain

Fig. 2 shows the boxplot for the obtained MEG values. Each box with 'whiskers' represent a handset/constellation combination where the median is shown as the middle line inside the box, the 25%-percentile Q_1 and 75%-percentile Q_3 as left and right vertical lines of the box, respectively. Data shown as '+' are outliers, defined as data points deviating more than $1.5 \times (Q_3 - Q_1)$ from the nearest percentile, Q_1 or Q_3. The dashed lines ('whiskers') indicate the extend of the data which are not outliers.

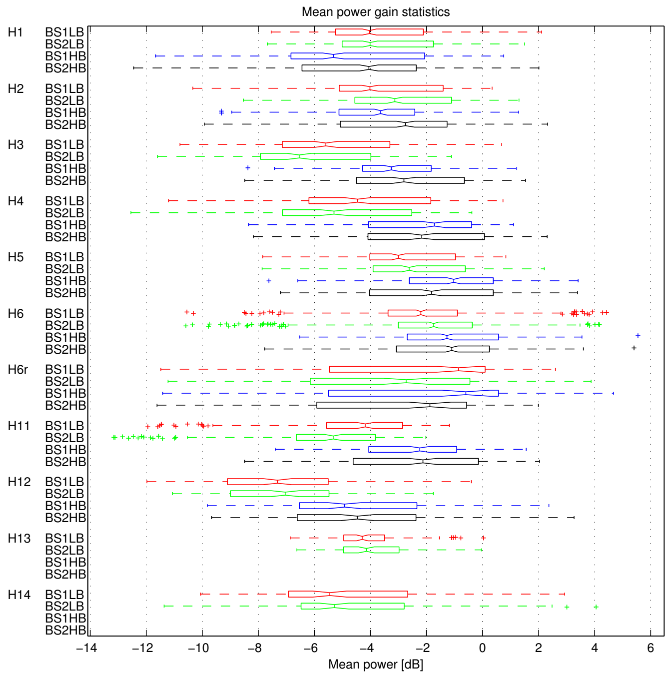

Fig. 2. Boxplot of the measured MEG values for all combinations of MIMO constellations (shown with color) and handsets.

A considerable variation is noticed among the handsets and the individual measurements, with differences up to about 16 dB. Considering only median values, the maximum difference is 6.5 dB (between H12 and H6r) for the LB and 4.7 dB (between H1 and H6r) for the HB.

It is further noticed that the MEG for a handset to some degree is similar for the different MIMO constellations, and that the MEG is similar for the two BSs on the same frequency band.

B. Branch Power Ratio

When holding the handsets the users will often cover the internal antennas and may thereby both absorb power and cause detuning *etc.* of the antennas. Fig. 3 shows the boxplots of the obtained BPR values.

Considering only the median values of the absolute BPR values, most values are in the range about 1–3.3 dB, with only H6r and H11 above for the LB.

C. Channel Correlation Coefficients

Fig. 4 shows the obtained statistics for the TxCC. The values are generally low for both bands of BS1, with median values below 0.3 in all cases. For BS2, the values are much higher with median values about 0.7 for the LB and about 0.9 for the HB. Since the Tx antenna arrays are identical for the two bases, the differences in TxCC can be attributed to the propagation environment. The generally higher TxCCs for BS2 are expected since, compared to BS1, BS2 is relatively

Presented at *The 8th European Conference on Antennas and Propagation (EuCAP 2014), April 2014. DOI: 10.1109/EuCAP.2014.6902413.*

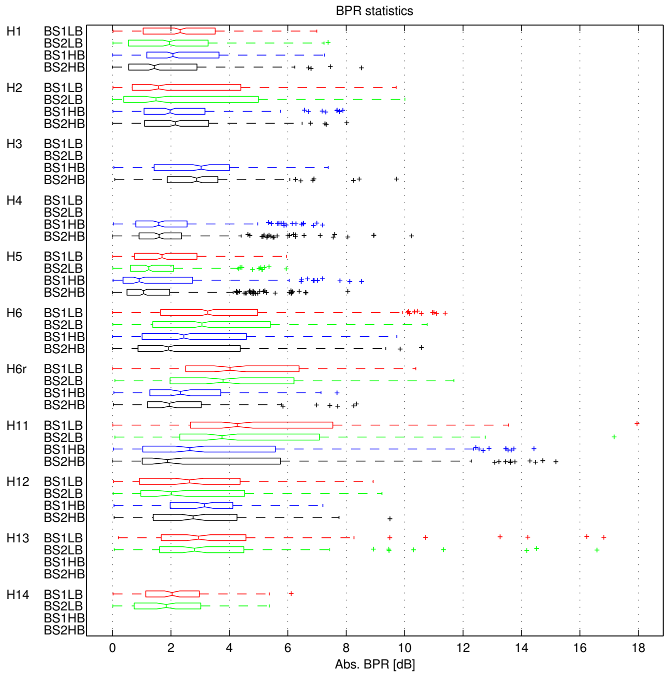

Fig. 3. Boxplot of the measured absolute BPR values for all combinations of MIMO constellations (shown with color) and handsets.

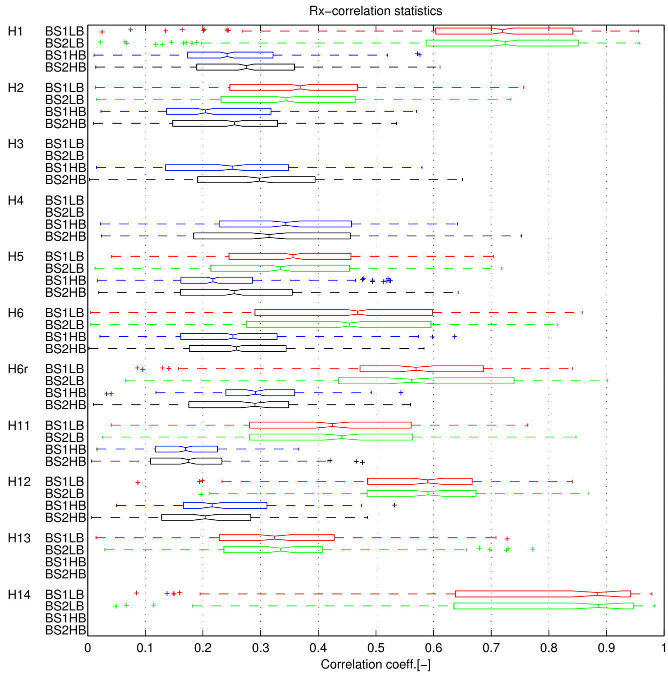

Fig. 5. Boxplot of the measured Rx-correlation coefficient (RxCC) for all combinations of MIMO constellations (shown with color) and handsets.

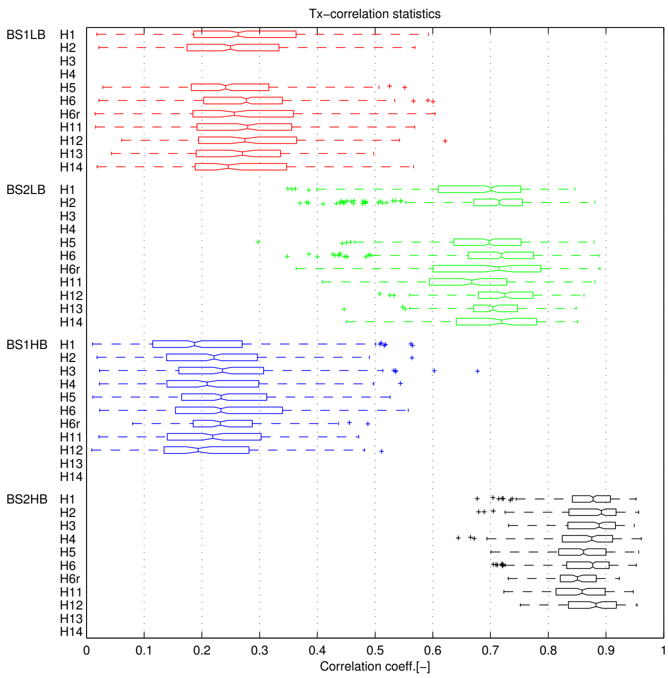

Fig. 4. Boxplot of the measured Tx-correlation coefficient (TxCC) for all combinations of MIMO constellations (shown with color) and handsets.

far away and in a high position with few nearby potentially scattering objects. Also as expected, the TxCC is roughly independent of the handset, with a maximum difference of 0.06 in the median values.

Fig. 5 shows boxplots for the RxCCs obtained with all combinations of handset and MIMO constellations. From the figure it is observed that the RxCCs are generally quite low with all the median RxCCs less than 0.6, except for H1 and H14 for the LB with median values 0.72 and 0.89, respectively.

For the dual-band handsets, the RxCC is always significantly lower for the HB than for the LB. Further, the median RxCC is less than 0.4 for all HB measurements.

Fig. 6 shows boxplots for the LxCCs. The majority of median values are less than 0.25, the only exceptions being 0.5 for H14/BS2LB and 0.33 for H6r/BS2LB. It is also noticed that the median values for BS2LB are always larger than the corresponding values for BS1LB. Similarly, the median values for BS2HB are always larger than the corresponding values for BS1HB.

D. Capacity

The capacities are computed using an SNR of 15 dB. Fig. 7 shows the boxplot of the obtained 10% OC values.

Note that H3 and H4 only have a single antenna at the LB, explaining the lower OC, compared to most of the other handsets for this band. H12, however, has two antennas on the LB, but low capacities are generally obtained, probably due to poor MEG performance and higher RxCC.

An overview of the OC results is given in Fig. 8. The 10% and 90% OC may be viewed as a measure of the capacity lower and upper bound, respectively. For both, a considerable variation is observed with differences of 2–3 bit/s/Hz over the handsets, and up to about 2 bit/s/Hz differences due to the BS location.

Note that the path loss is generally higher on the HB than on the LB. Therefore more transmit power is needed in this band to maintain the same SNR as on the LB.

Presented at *The 8th European Conference on Antennas and Propagation (EuCAP 2014), April 2014. DOI: 10.1109/EuCAP.2014.6902413.*

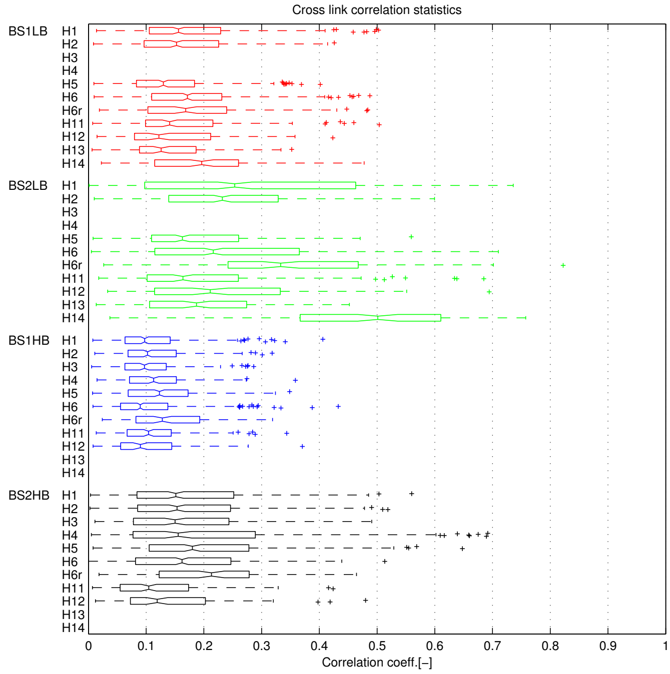

Fig. 6. Boxplot of the measured cross-link correlation coefficient (LxCC) for all combinations of MIMO constellations (shown with color) and handsets.

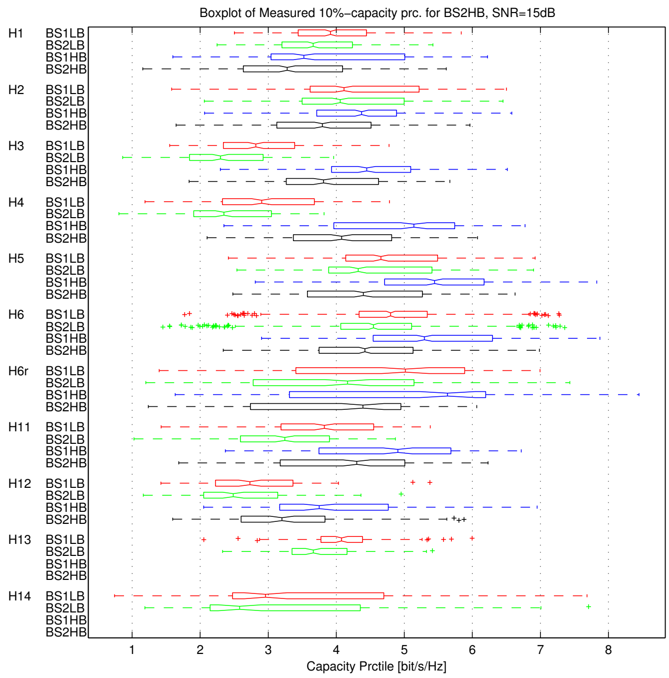

Fig. 7. Boxplot of the measured 10% outage capacity (OC) for all combinations of MIMO constellations (shown with color) and handsets.

V. Conclusion

The variation in mean effective gain (MEG) was up to about 16 dB for the same handset, and among the handsets the maximum difference in the median MEG was 6.5 dB (low band (LB)) and 4.7 dB (high band (HB)). The absolute branch power ratio (BPR) values were up to about 13 dB, with median

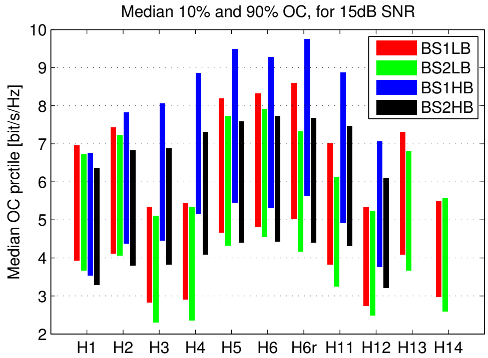

Fig. 8. Median outage capacity (OC) obtained with different users, orientations, and UCs. The min/max of each bar is defined by the median 10% OC and the median 90% OC for the particular combination of handset (in groups along horizontal axis) and MIMO constellation (shown with color).

values in the range 0.9–4.3 dB. The Tx-correlation coefficient (TxCC) was low for BS1, with median values less than 0.3. Due to the different location, the median TxCC is higher for BS2, about 0.7 and 0.9 for the LB and HB, respectively. The median Rx-correlation coefficient (RxCC) was less than 0.6 on the LB, except for two handsets with up to 0.89. On the HB the RxCC was always less than 0.4. The median cross-link correlation coefficients (LxCCs) were generally less than 0.25, and always less than 0.5. For an SNR of 15 dB, the median 10%-outage capacity was 2.3–5.6 bit/s/Hz, depending on the band, BS and handset.

References

[1] D. Gesbert, H. Bolcskei, D. Gore, and A. Paulraj, "Outdoor MIMO wireless channels: models and performance prediction," *IEEE Trans. Commun.*, vol. 50, no. 12, pp. 1926–1934, Dec. 2002.

[2] G. F. Pedersen, J. Ø. Nielsen, K. Olesen, and I. Z. Kovacs, "Measured variation in performance of handheld antennas for a large number of test persons," in *48th Vehicular Technology Conf., VTC '98.* IEEE, May 1998, pp. 505–509.

[3] W. Kotterman, G. Pedersen, and K. Olesen, "Capacity of the mobile MIMO channel for a small wireless handset and user influence," in *Personal, Indoor and Mobile Radio Communications, 2002. The 13th IEEE Int. Symp. on*, vol. 4, Sep. 2002, pp. 1937–1941.

[4] F. Harrysson, J. Medbo, A. Molisch, A. Johansson, and F. Tufvesson, "Efficient experimental evaluation of a MIMO handset with user influence," *IEEE Trans. Wireless Commun.*, vol. 9, no. 2, pp. 853–863, Feb. 2010.

[5] J. Ø. Nielsen, B. Yanakiev, I. Bonev, M. Christensen, and G. Pedersen, "User influence on MIMO channel capacity for handsets in data mode operation," *IEEE Trans. Antennas Propag.*, vol. 60, no. 2, pp. 633 –643, Feb. 2012.

[6] B. Yanakiev, J. Nielsen, M. Christensen, and G. Pedersen, "Long-range channel measurements on small terminal antennas using optics," *IEEE Trans. Instrum. Meas.*, vol. 61, no. 10, pp. 2749 –2758, Oct. 2012.

[7] J. Ø. Nielsen, J. B. Andersen, P. C. F. Eggers, G. F. Pedersen, K. Olesen, E. H. Sørensen, and H. Suda, "Measurements of indoor 16×32 wideband MIMO channels at 5.8 GHz," in *Proceedings of the 2004 Int. Symp. on Spread Spectrum Techniques and Applications (ISSSTA 2004)*, 2004, pp. 864–868.

[8] B. Yanakiev, "MIMO antennas for small mobile devices," Ph.D. dissertation, Department of Electronic Systems, Aalborg University, Denmark, 2011, ISBN 978-87-92328-70-0.

[9] D. Gesbert, M. Shafi, D. shan Shiu, P. J. Smith, and A. Naguib, "From theory to practice: An overview of MIMO space-time coded wireless systems," *IEEE J. Sel. Areas Commun.*, vol. 21, no. 3, pp. 281–302, Apr. 2003.

Presented at *The 8th European Conference on Antennas and Propagation (EuCAP 2014), April 2014. DOI: 10.1109/EuCAP.2014.6902413.*