ASSESSMENT AND COMPARISON OF TOTAL RF-EMF EXPOSURE IN FEMTOCELL AND MACROCELL BASE STATION SCENARIOS

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Running title: Comparison of FBS and MBS exposure

Abstract

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The indoor coverage of a mobile service can be drastically improved by the deployment of an indoor femtocell base station (FBS). However, the impact of its proximity on the total exposure of the human body to radio-frequency (RF) electromagnetic fields (EMF) is unknown. Using a framework designed for the combination of near-field and far-field exposure, the authors assessed and compared the RF-EMF exposure of a mobile phone user that is either connected to an FBS or a conventional macrocell base station while in an office environment. It is found that, in average macrocell coverage and mobile phone use-time conditions and for UMTS (Universal Mobile Telecommunications System) technology, the total exposure can be reduced by a factor 20 to 40 by using an FBS, mostly due to the significant decrease in the output power of the mobile phone. In general, the framework presented in this study can be used for any exposure scenario, featuring any number of technologies, base stations and/or access points, users, and duration.

INTRODUCTION

Recent advancements in mobile technologies include the development of the femtocell base station (FBS), a miniature base station specifically designed for the enhancement of the coverage and capacity of a mobile service in a small, indoor environment (e.g., an office, or a home). Generally installed in rooms readily accessible to the users of the mobile service, the burden of the FBS on the users' exposure to radio-frequency (RF) electromagnetic fields (EMF), however, is uncertain. Furthermore, the general public might feel an inhibition about the deployment of a base station in their home or office(1).

In general, RF-EMF exposure can be divided into two categories, according to proximity of the RF-EMF source to the body. On the one hand, people are exposed to near-field (NF) sources, which are generally controlled by the user, and operated in close vicinity to the body (e.g., mobile phones, tablets, etc.). Because of its proximity to the body, an NF source causes a highly-varying localized exposure (e.g., in the head or in the leg) that can temporarily reach relatively high values in terms of the specific absorption rate (SAR). On the other hand, the population is exposed to far-field (FF) sources, such as base stations and (radio) transmitters, which are usually located much farther away from the body, and emit a near-continuous background radiation that impacts the whole body, but with exposure levels that are relatively low compared to the levels caused by NF sources (in operation).

As far as the authors know, there have been only two previous studies on the assessment of RF-EMF exposure from an FBS. In Ref. (2), the (received and transmitted) signal powers of a mobile phone were compared between FBS and MBS scenarios, while in Ref. (3), the relative exposure of a mobile-phone user in a home environment is calculated in the presence and absence of an FBS, using a power model.

In this study, the authors take a different approach to quantify the effect of the FBS's presence on the total RF-EMF exposure, based on the framework presented in Ref. (4), which combines the contributions of FF and NF sources to the total exposure and introduces a new exposure metric, i.e., the RF-EMF dose absorbed by the human body. The approach is applied to a scenario in which a single mobile-phone user in an office environment is either connected to a regular (outdoor) macrocell base station (MBS) or to the introduced (indoor) FBS. Due to the proximity of the FBS to the user, on the one hand, the user's mobile phone is expected to transmit at a lower output power compared to a connection with an MBS, effectively reducing the NF exposure of the user[2,3], while simultaneously, on the other hand, there will be an increased FF contribution to the total exposure[3]. The authors assess in which use case (i.e., considering the use-time of the mobile phone and the initial MBS coverage) the deployment of an FBS would effectively result in a decrease of the total exposure. It should be noted that only the *whole-body* exposure is considered here, and that the assessment of the *localized* exposure is outside the scope of this study.

MATERIALS AND METHOD

Measurements

Base Stations. The femtocell base station (FBS) considered in this study was of the type ePico3801B (Huawei, Shenzhen, Guangdong, China), with dimensions of approximately 20 cm x 5 cm x 15 cm, plus an antenna with a length of approximately 15 cm on top. The FBS used the UMTS (Universal Mobile Telecommunications System) technology, with a downlink (i.e., the signal from the base station to the mobile phone) frequency of 2151.6 MHz, and an uplink (i.e., the signal from the mobile phone to the base station) frequency of 1957.6 MHz.

Furthermore, the FBS had a fixed output power, P_{FBS}, of 10 mW; no power control algorithms were enabled.

Concerning the user's connection to a macrocell base station (MBS), the authors considered the UMTS signal that was present in the building, with a downlink frequency of 2162 MHz, and a corresponding uplink frequency of 1972 MHz.

Measurement Device. The authors used as measurement device a Nokia N95 mobile phone (Nokia, Espoo, Finland), equipped with a Field Test Display (FTD) program, with which they were able to monitor the transmit power of the mobile phone (indicated as *TX*), as well as the power received by the phone (indicated as *RSSI*, i.e., the *Received Signal Strength Indication*). Both powers were measured in dBm (decibel milliwatt), which relates to mW according to the following formula,

$$P[\text{dBm}] = 10 \times \log_{10}\left(\frac{P[\text{mW}]}{1\ \text{mW}}\right). \tag{1}$$

In other words, the FBS had an output power of 10 dBm.

Scenarios. The main exposure scenario consisted of a long corridor (approximately 60 m), situated on the third floor of an office building, and shown in Figure 1. The FBS was positioned at one end of the corridor, above a door (at a height of approximately 2 m). A phone call (25% voice) was set up through the UMTS connection to either the MBS (this scenario is further denoted as *MBS*-corridor) or the FBS (further denoted as *FBS-corridor*), and measurements were performed at regular intervals along the corridor. A blueprint of this office environment, with the position of the FBS indicated with a square, and the measurement locations of *FBS-corridor* with dots, is shown in Figure 1. For *FBS*-corridor, the first position was at 0.5 m from the FBS, and the first 18 m of the corridor were within line-of-sight (LOS) of the FBS (in total, 28 measurements were performed in LOS), while farther positions were non-line-of-sight (NLOS) (22 measurements). For *MBS-corridor*, measurements were performed at 20 positions along the corridor. In order to study MBS scenarios with worse coverage, additional measurements were performed on a staircase (third to second floor of the office building) (scenario *MBS-staircase*) and in the underground parking of the office building (scenario *MBS-parking*). However, no FBS could be deployed at these locations. It should further be noted that no measurement location was in LOS of an MBS.

Measurement Method. At each measurement location, the maximum and minimum *TX* values, and the *RSSI* value were captured (after they had stabilized) along four orthogonal orientations, after which the averages of the four orientations were retained as measurement values at the respective measurement location. This averaging was done to account for the influence of the mobile antenna directivity[(2)]. The mobile phone was held horizontally by the experimenter on the palm of his hand, at 1.3 m above the floor, and 0.3 m from the body (the upper arm was held to the body, the lower arm at a 90 degrees angle). It should be noted that *RSSI* is merely a measure of the power present in the received (downlink) signal, and that there was no direct link known beforehand between the measured *RSSI* value at location *i* and the *power flux density* of the downlink signal, S_{DL} (in W/m^2) (further denoted as *power density*) at this location. The authors solved this issue by performing accurate spectrum analyzer measurements of the power density, and calibrating the measured $RSSI_i$ to the correct power densities, $S_{DL,i}$. The measured *TX* values, on the other hand, were equal to the uplink power values, P_{UL} (in dBm, or in mW).

Exposure Comparison

In Ref. (4) a new RF-EMF exposure framework was presented, combining the whole-body exposure due to both NF and FF sources into a single exposure proxy, namely the *dose*, i.e., the absorbed RF-EMF power in the human body during a certain (exposure) time, with unit J/kg (Joules per kilogram of body mass). This framework makes it possible to objectively compare different scenarios to find a minimum in terms of human exposure to RF-EMF.

Dose Calculation. Since all *FBS-corridor* measurement positions were in the far field of the FBS[5] the far-field contribution to the exposure can be identified with the downlink (DL) contribution, and the near-field contribution with the uplink (UL) contribution. Hence, the total dose, *D*, can be written as

$$D = D_{DL} + D_{UL}, \quad (2)$$

with D_{DL} the downlink dose (due to far-field sources), and D_{UL} the uplink dose (due to near-field sources).

The downlink dose, D_{DL} (J/kg), is calculated as follows[4],

$$D_{DL} = T_{exp} \times SAR_{DL} \times S_{DL}, \quad (3)$$

with T_{exp} the exposure time in s (i.e., the time the exposed person spends in the considered exposure scenario), SAR_{DL} is the normalized (to an incident power density, *S*, of 1 W/m^2) *whole-body* SAR due to the exposure to the base station downlink signal, and S_{DL} is the power density of the incident downlink signal (in W/m^2). From simulations[4], SAR_{DL} was found to be 3 mW/kg per 1 W/m^2 incident power density for a frequency of 2150 MHz, and as the FBS and MBS in this study have a similar downlink frequency (2151.6 and 2162 MHz, respectively), this value was used in Equation (3) throughout the calculations. Because an office scenario is considered, an exposure time T_{exp} of 8 hours is assumed.

As there is no direct link between the power density of the incident downlink signal, S_{DL}, and the RSSI values recorded with the mobile phone of this signal, accurate spectrum analyzer (SA) measurements of the power density were performed along the corridor in LOS conditions (this was only done for the *FBS-corridor* scenario), in order to calibrate the power density values derived from the recorded RSSI values (which are measured in dBm) (following International Telecommunication Union – Radiocommunications (ITU-R) Recommendation SM.1708-1[6]), $S_{DL,RSSI}$ (in W/m^2), to the correct power density values, S_{DL} (in W/m^2),

$$S_{DL} = f_{cal} \times S_{DL,RSSI}, \quad (4)$$

with f_{cal} a dimensionless calibration factor.

The SA setup used for the calibration measurements consisted of a PCD 8250 antenna (ARC Seibersdorf Research GmbH, Seibersdorf, Austria), with a dynamic range of 1.1 mV/m - 100 V/m and a frequency range of 80 MHz - 3 GHz, in combination with an SA of type R&S FSL6 with frequency range 9 kHz – 6 GHz (Rohde & Schwarz, Zaventem, Belgium). The measurement uncertainty (the expanded uncertainty evaluated using a confidence interval of 95%) for the considered setup is ± 3 dB[7,8].

Secondly, the uplink dose, D_{UL}, (J/kg), is calculated as follows[4],

$$D_{UL} = T_{use} \times SAR_{UL} \times P_{UL}, \quad (5)$$

with T_{use} is the use-time or call-time in s of the mobile phone during the total exposure time T_{exp} defined above in Equation (3), SAR_{UL} the normalized (to an output power of the mobile phone of 1 W) *whole-body* SAR due to the exposure to the mobile device's uplink signal, and P_{UL} the average power (in W) of the uplink signal during the scenario. In the Qualifex study[9], an average call-time, T_{use}, of 25.6 min/week was found, while in Ref. (3), an average call of 16.45 min/day was used (5 calls of 3.29 min each). In this study, the call-time is varied between 0 and 16.45 min/day (or 5.5 min/8 h). From simulations with a head model[(4)], a SAR_{UL} of 4.95 mW/kg per 1 W output power was found for a frequency of 1950 MHz. Since the FBS and the MBS have a similar uplink frequency (1957.6 and 1972 MHz, respectively), this value was used in Equation (5) throughout the calculations.

RESULTS AND DISCUSSION

Measurements

The measurements performed in this study (both with the mobile phone and the SA) are summarized inTable 1. Additionally, Figure 2 displays the transmitted (*TX*) and the received power (*RSSI*) (measured with the mobile phone) as a function of the distance (from the FBS) along the corridor for both *MBS-corridor* and *FBS-corridor*. As expected, the *RSSI* and *TX* measured in the *FBS-corridor* scenario show on average a steady decrease and a steady increase, respectively, when moving away from the FBS, while for *MBS-corridor*, they seem to vary only slightly along the corridor.

In the *FBS-corridor* scenario, a total of 50 measurements were performed, with 28 positions (up to 18 m distance) in LOS of the FBS (see also Figure 1), a division that can also be observed in Figure 2, where a sudden drop in RSSI and a simultaneous rise in TX is observed at 18 m. On average, we observed an *RSSI* of -66 dBm and a *TX* of -33 dBm along the corridor (Table 1; up to 63 m from the FBS), with maximum values of -55 dBm and -27 dBm, and minima of -87 dBm and -55 dBm, respectively.

In the *MBS-corridor* scenario, 20 measurements were performed along the corridor, between 2 and 63 m from the FBS. Both the *RSSI* and *TX* varied within a span of approximately 10 dB, the *RSSI* from -89 to -79 dBm, and *TX* from -21 to -13 dBm, with respective averages of -84 dBm and -16 dBm (Table 1). These values are close to the median transmitted (-20 dBm) and received (-80 dBm) powers reported in Ref. (10) for UMTS. Hence, *MBS-corridor* can be more or less considered as an average MBS exposure scenario. Additional MBS measurements were performed in two more secluded areas: the *MBS-staircase* and *MBS-parking* scenarios. The latter represented the worst-case scenario: an *RSSI* of -102 dBm and a *TX* of +23 dBm were measured just before the connection dropped (Table 1). On the staircase, values of -95 dBm and -2 dBm were measured for *RSSI* and *TX*, respectively. The UMTS signal reception in these scenarios is thus 11 to 18 dB lower than the average reception in the corridor.

The ranges for *TX* and *RSSI* found in this study can be compared to those described in Ref. (10) for UMTS received and transmitted powers (different configurations: here FBS and MBS, in Ref. (10) only MBS), with the *RSSI* ranging from -102 dBm (worst case, from MBS) to -56 dBm (best case, from FBS) (in Ref. (10): -106 dBm to *-27 dBm*), and the *TX* from -55 dBm (FBS) to +23 dBm (MBS) (in Ref. (10): -57 dBm to +23 dBm). Although there is a difference of 30 dB in maximum *RSSI*, the minimum *TX* values are similar, which means that from a certain point on, the improvement of the base station signal reception stops resulting in an improvement of the mobile phone's output power, with respect to the dose induced in the mobile phone user. Hence, an optimal FBS output power can be found which minimizes the dose induced in the average user.

For the calibration of the *FBS-corridor RSSI* measurements, 13 SA measurements were performed at distances from 0.3 to 15 m from the FBS (see also Table 1). On average, an electric-field strength of 0.16 V/m was observed (range from 0.28 V/m at 2.5 m to 0.07 V/m at 10 m), which is far below the ICNIRP reference level of 61 V/m at the considered FBS downlink frequency of 2151.6 MHz[11].

Calibration

The SA measurements were used to calibrate the power densities derived from the RSSI measurements with the mobile phone. The calibration factor, f_{cal}, defined in Equation (4), was found to be 98.6. The results of the calibration are shown in Figure 3. The same trend can be observed for both the SA measurements and the calibrated mobile phone measurements, i.e., a decrease in power density farther from the FBS. Overall, SA measurements and calibrated mobile phone measurements seem to agree quite well, with an average calibration error of 4.3 dB. However, both the SA and mobile phone data show a random variation around this value.

Exposure Comparison

The results of the dose calculations as a function of the mobile-phone use-time, T_{use}, are shown in Figure 4, while *The uplink dose, D_{UL}, in the FBS scenario is independent of the output power of the FBS, P_{FBS}.

Table 2 gives an overview of the downlink doses and the uplink doses calculated for the average use-times of 9.1 s/h[9] and 41.3 s/h[3] found in the literature.

For all three MBS scenarios, the dose is entirely dependent on T_{use}, or in other words, the user's total exposure is dominated by his exposure to the mobile phone's uplink signal. D_{DL}

ranges from 0.3 x 10^{-3} mJ/kg (MBS-parking, RSSI -102 dBm) and 20 x 10^{-3} mJ/kg (MBS-corridor, average RSSI -84 dBm), while for a T_{use} of 9.1 s/h, the uplink exposure in *The uplink dose, D_{UL}, in the FBS scenario is independent of the output power of the FBS, P_{FBS}.

Table 2 already amounts to doses between 36 mJ/kg (*MBS-corridor*, average *TX* -16 dBm) and 259 J/kg (*MBS-parking*, *TX* +23 dBm)!

Although during the measurements, P_{FBS} was constant at 10 dBm, for the *FBS-corridor* scenario, additional calculations were performed for FBS output powers of 0 dBm (1 mW) and 20 dBm (100 mW, assumed to be the highest output power the FBS can exhibit). The authors assumed that because there was no change in the effective path loss between base station and mobile phone, the *TX* values measured in the *FBS-corridor* scenario (in which P_{FBS} is 10 dBm) would have been identical if the FBS had radiated at these powers, and moreover, that the *RSSI* values would have merely been shifted by -10 or +10 dB, respectively.

It is clear from Figure 4 that for *FBS-corridor* (black lines), *D* is dominated by the downlink exposure for small T_{use}, as *D* is constant until a certain T_{use} is reached. The exact value of T_{use} for which D_{UL} becomes a significant factor naturally depends on P_{FBS}, and is approximately 1 s/h for P_{FBS} 10 dBm.

Assuming a minimum P_{FBS} of 0 dBm, the user's total exposure will only be higher in case of the deployment of an FBS if he does *not* use his mobile phone (T_{use} = 0 s), due to the elevated downlink exposure in the presence of an FBS. However, even with little mobile-phone use, the *MBS-corridor*'s total exposure will surpass the *FBS-corridor*'s, e.g., at a T_{use} of approximately 0.3 s/h for a P_{FBS} of 10 dBm, and 2.5 s/h for a P_{FBS} of 20 dBm (Figure 4; for *MBS-parking* and *MBS-staircase*, the respective T_{use} will of course be much lower). Since the latter is equal to about 7 min per week, which is far less than the average call-time of 26.1 min per week found in Ref. (9), one can conclude that the FBS deployment will almost certainly result in a *reduction of the user's total* whole-body *exposure*. On average, comparing *MBS-corridor* and *FBS-corridor* with P_{FBS} = 10 dBm, and T_{use} = 9.1 or 41.3 s/h, the magnitude of the reduction is found to be a factor 21 or 41.

Discussion

The authors experimentally demonstrated that the indoor deployment of a femtocell base station could reduce the RF-EMF exposure of a mobile phone (UMTS technology) user by a factor 20 to 40, considering average macrocell coverage and mobile phone use-time conditions. In order to assess and compare the total whole-body exposure of the mobile-phone user, a framework was used to combine the downlink and uplink exposure into a single exposure proxy: the dose (the RF-EMF energy absorbed by the whole body during the exposure time).

The authors assumed that the output power of the mobile phone at a certain location would be the same if the phone was held in front of the body (as was done in the study) or close to the head (as was assumed in the dose calculations). The former configuration was preferred in this study in order to be able to read the measured power values. Future research will assess the difference in output powers for different configurations (e.g., to the ear, or in the pocket).

It should further be noted that if instead of UMTS, GSM900 or GSM1800 (Global System for Mobile Communications, at 900 or 1800 MHz) were considered, the NF contributions to the total exposure would have been higher, due to the higher average output power of GSM mobile phones(10). This would especially effect the dose in *MBS* scenarios.

The *localized* exposure due to the mobile phone was not considered here. A similar approach can however be taken to calculate the localized dose, e.g., by replacing SAR_{UL} by the maximum SAR in 10 g of tissue, $SAR_{10g,max}$, as measured by e.g., the FCC, and weight it by the ratio between the mobile phone's TX and TX_{max}[10].

Essentially, the average specific absorption rate (SAR) in the whole body of a certain user is determined during a particular exposure scenario, and multiplied by the time spent by the user in this scenario. Hence, it is possible to compare our results with the SAR limits issued by ICNIRP[11] (satisfying the limits, as stated above). However, the authors believe that by taking into account the cumulative exposure (through T_{use} and T_{exp}), the framework presented herein can be of important use in epidemiological studies. While these studies[12] often use cumulative call-time as an exposure proxy, they do not consider the output power of the mobile phone (as was done in this study), which is essential for a correct classification of the total exposure of a user.

CONCLUSIONS

The impact of the use of an indoor femtocell base station on a mobile phone user's total exposure to radio-frequency electromagnetic fields is assessed in case of an office scenario. It is found that, unless the mobile phone is not used, even for an average macrocell coverage, the deployment of a femtocell base station could drastically reduce the user's RF-EMF exposure, although the magnitude of the reduction depends heavily on the mobile-phone use-time and the quality of the conventional macrocell base station's signal, and is found to be a factor of 20 to 40 in average conditions. In general, the framework presented in this study can be used for any exposure scenario, featuring any number of technologies, base stations and/or access points, users, and duration.

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REFERENCES

1. World Health Organization (WHO). *Base Stations and Wireless Networks : Exposures and Health Consequences*. In Proceedings of the International Workshop on Base Stations and Wireless Networks: Exposures and Health Consequences. Geneva, Switzerland (2005).

2. Boursianis, A., Vanias, P., Samaras, T. *Measurements for assessing the exposure from 3G femtocells*. Radiat. Prot. Dosim. **150**, 158–167 (2012).

3. Zarikoff, B., Malone, D. *A comparison of RF exposure in macro- and femtocells*. Health Phys. **105**, 39–48 (2013).

4. Lauer, O., Frei, P., Gosselin, M.-C., Joseph, W., Röösli, M., Fröhlich, J. *Combining near- and far-field exposure for an organ-specific and whole-body RF-EMF proxy for epidemiological research: a reference case*. Bioelectromagnetics **34**, 366-374 (2013).

5. Joseph, W., Martens, L. *The influence of the measurement probe on the evaluation of electromagnetic fields*. IEEE Trans. EMC **43**, 339–349 (2003).

6. ITU-R Recommendation SM.1708-1. *Field-strength measurements along a route with geographical coordinate registrations*. http://www.itu.int/dms_pubrec/itu-r/rec/sm/R-REC-SM.1708-1-201109-I!!PDF-E.pdf (2011) (Last accessed on September 5, 2013).

7. CENELEC (European Committee for Electrotechnical Standardization). *TC 106x WG1 EN 50492 in situ. Basic standard for the in-situ measurement of electromagnetic field strength related to human exposure in the vicinity of base stations.* Brussels, Belgium (2008).

8. Joseph, W., Verloock, L., Goeminne, F., Vermeeren, G.G., Martens, L. *Assessment of RF exposures from emerging wireless communication technologies in different environments*. Health Phys. **102**, 161-172 (2012).

9. Mohler, E., Frei, P., Aydin, A., Bürgi, A., Röösli, M. *Personal exposure to high-frequency electromagnetic fields in the region of Basel (Switzerland): An overview of the Qualifex study*. Umweltmed. Forsch. Prax. **14**, 329–338 (2009).

10. Gati, A., Conil, E., Wong, M.-F., Wiart, J. *Duality between uplink local and downlink whole-body exposures in operating networks.* IEEE Trans. EMC **52**, 829–836 (2010).

11. International Commission on Non-Ionizing Radiation Protection (ICNIRP). *Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz).* Health Phys. **74**, 494–522 (1998).

12. Cardis, E., Richardson, L., Deltour, I., et al. *The INTERPHONE study: design, epidemiological methods, and description of the study population.* Eur J Epidemiol **22**(9), 647–64 (2007).

LIST OF CAPTIONS

Table 1: Overview of the measurements performed in this study; using a mobile phone and a spectrum analyzer.

[*] The uplink dose, $\boldsymbol{D_{UL}}$, in the FBS scenario is independent of the output power of the FBS, $\boldsymbol{P_{FBS}}$.

Table 2: Downlink and uplink doses of the considered exposure scenarios.

Figure 1: Blueprint of the office building (90 m x 17 m), with indication of *FBS-corridor*'s measurement locations (dots), and the location of the FBS (black square). Grey lines represent concrete walls, black lines layered drywall (except the outer walls, which are metallic and contain windows).

Figure 2: Measurements of the transmitted power (*TX*, full lines) and received power (*RSSI*, dashed lines) for both the *FBS-corridor* (black), and the *MBS-corridor* (grey) scenarios. The vertical dash-dotted line, at which a rise in TX_{FBS} and a simultaneous drop in $RSSI_{FBS}$ of 10 dB are observed, signifies the change of LOS to NLOS conditions for *FBS-corridor*. Furthermore, as was expected, there is a steady increase in *TX* and a concurrent decrease in *RSSI* when moving away from the FBS. The *TX* and *RSSI* values measured for *MBS-corridor* vary within a 10 dB range, but no trend is observed along the corridor.

Figure 3: Calibration of the power densities derived from the *RSSI* values measured with the mobile phone (MP), using spectrum analyzer (SA) measurements between 0.5 and 15 m from the FBS.

Figure 4: Doses (in mJ/kg) calculated for the considered exposure scenarios (*FBS-corridor* (with P_{FBS} set to 0, 10 or 20 dBm), *MBS-corridor*, *MBS-staircase*, *MBS-parking*) using average uplink and downlink powers, but varying the use-time, T_{use}, of the mobile phone. The dash-dot lines represent the average call-times of 9.31 s/h[9] and 41.3 s/h[3] found in the literature.

	# meas.	Distance range		Min.	Dist.	Max.	Dist.	Mean
MOBILE PHONE								
MBS-corridor	20	2 – 63 m	*RSSI*	-89 dBm	26.2 m	-79 dBm	39.0 m	-84 dBm
			TX	-21 dBm	12.0 m	-13 dBm	26.2 m	-16 dBm
FBS-corridor	50	0.5 – 63 m	*RSSI*	-87 dBm	63.0 m	-55 dBm	1.5 m	-66 dBm
			TX	-55 dBm	3.0 m	-27 dBm	59.0 m	-33 dBm
MBS-staircase	1	--	*RSSI*	--	--	--	--	-95 dBm
			TX	--	--	--	--	-2 dBm
MBS-parking	1	--	*RSSI*	--	--	--	--	-102 dBm
			TX	--	--	--	--	+23 dBm
SPECTRUM ANALYZER	13	0.3 – 15 m	*E*	0.07 V/m	10.0 m	0.28 V/m	2.5 m	0.16 V/m

MBS = macrocell base station, FBS = femtocell base station.
# meas. = number of measurements. Min. = minimum. Max. = maximum. Dist. = distance from the FBS along the corridor.

Table 1

Scenario	D_{DL} **(mJ/kg)**	D_{UL} ***(mJ/kg)*** $T_{use} = 9.1$ ***s/h***	D_{UL} ***(mJ/kg)*** $T_{use} = 41.3$ ***s/h***
FBS-corridor (P_{FBS} = 10 dBm)	1	0.7*	3*
FBS-corridor (P_{FBS} = 0 dBm)	0.1		
FBS-corridor (P_{FBS} = 20 dBm)	13		
MBS-corridor	0.02	36	165
MBS-staircase	0.002	819	3 715
MBS-parking	0.0003	258 845	1 174 756

*The uplink dose, D_{UL}, in the FBS scenario is independent of the output power of the FBS, P_{FBS}.

Table 2

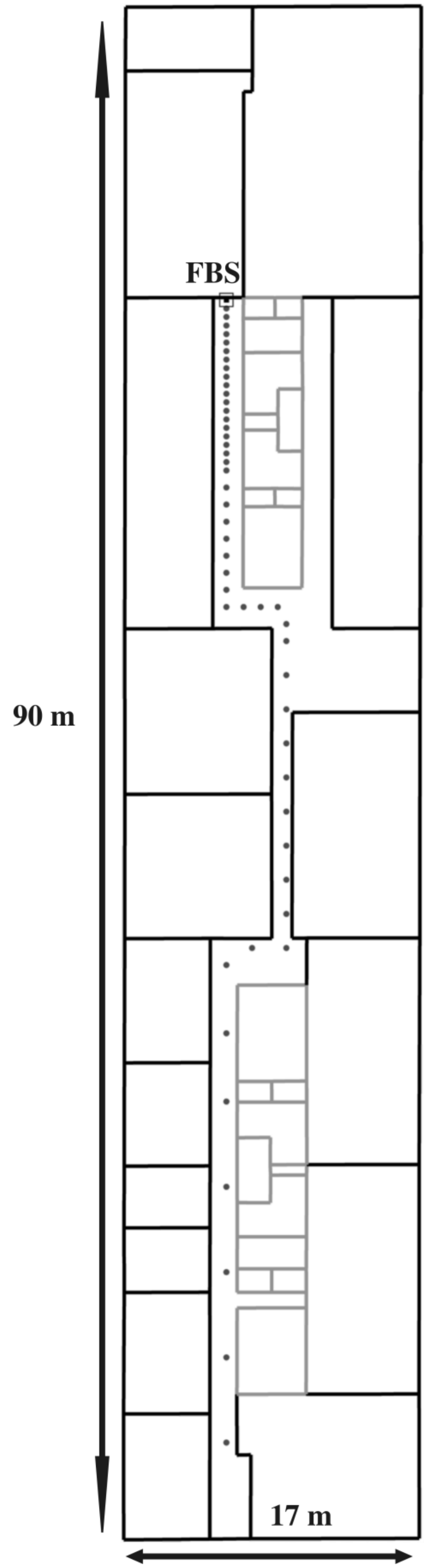
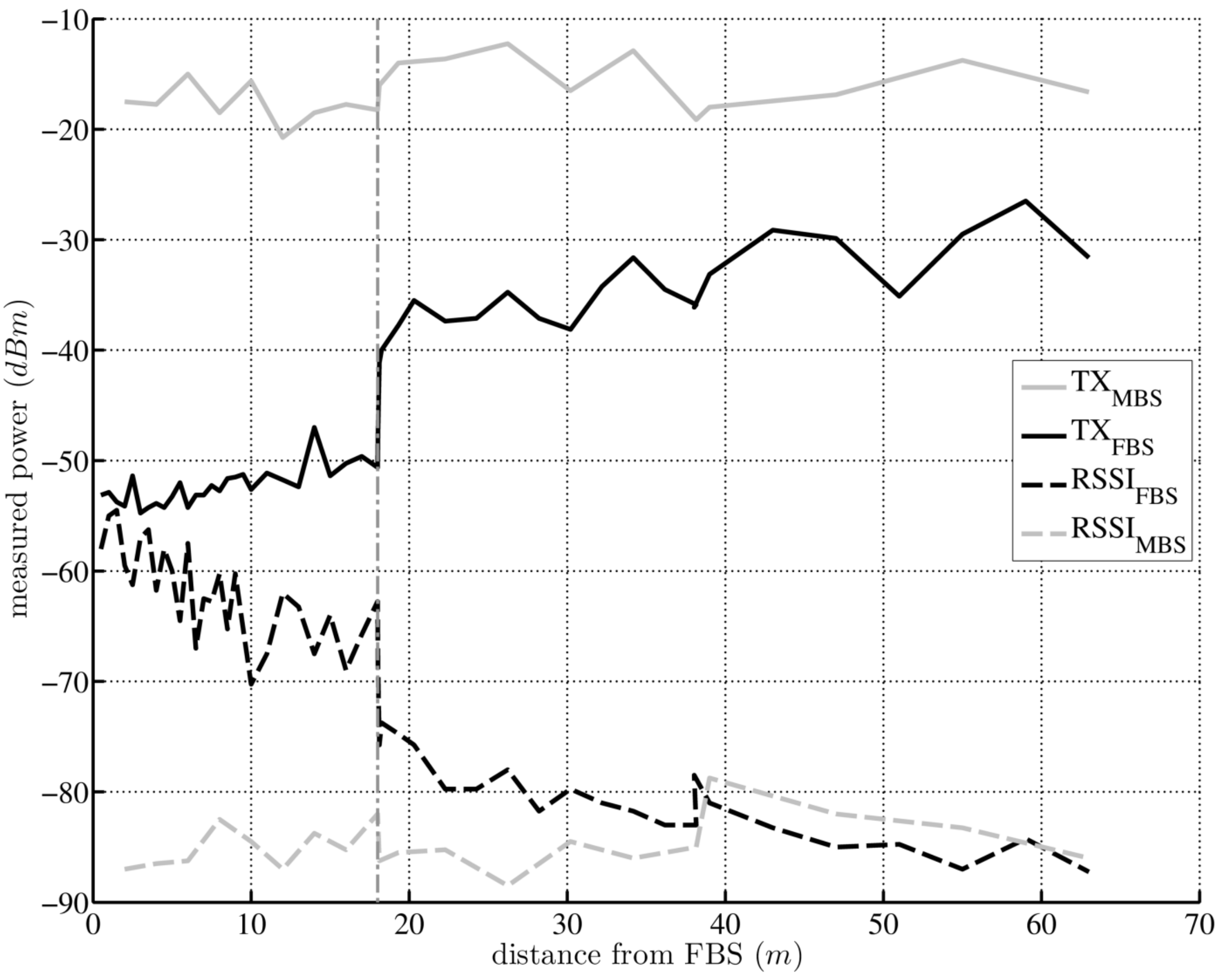


Figure 1



−10
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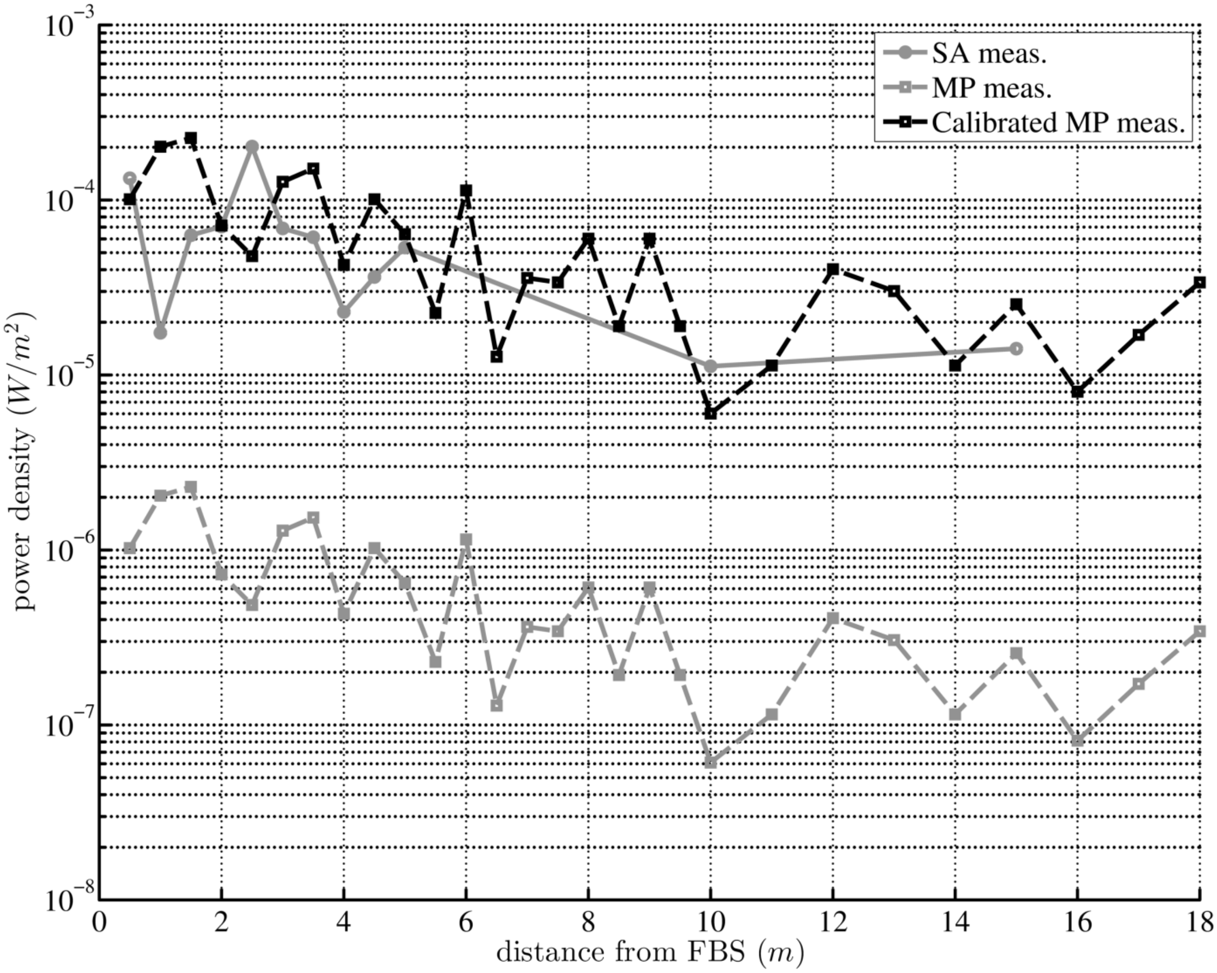
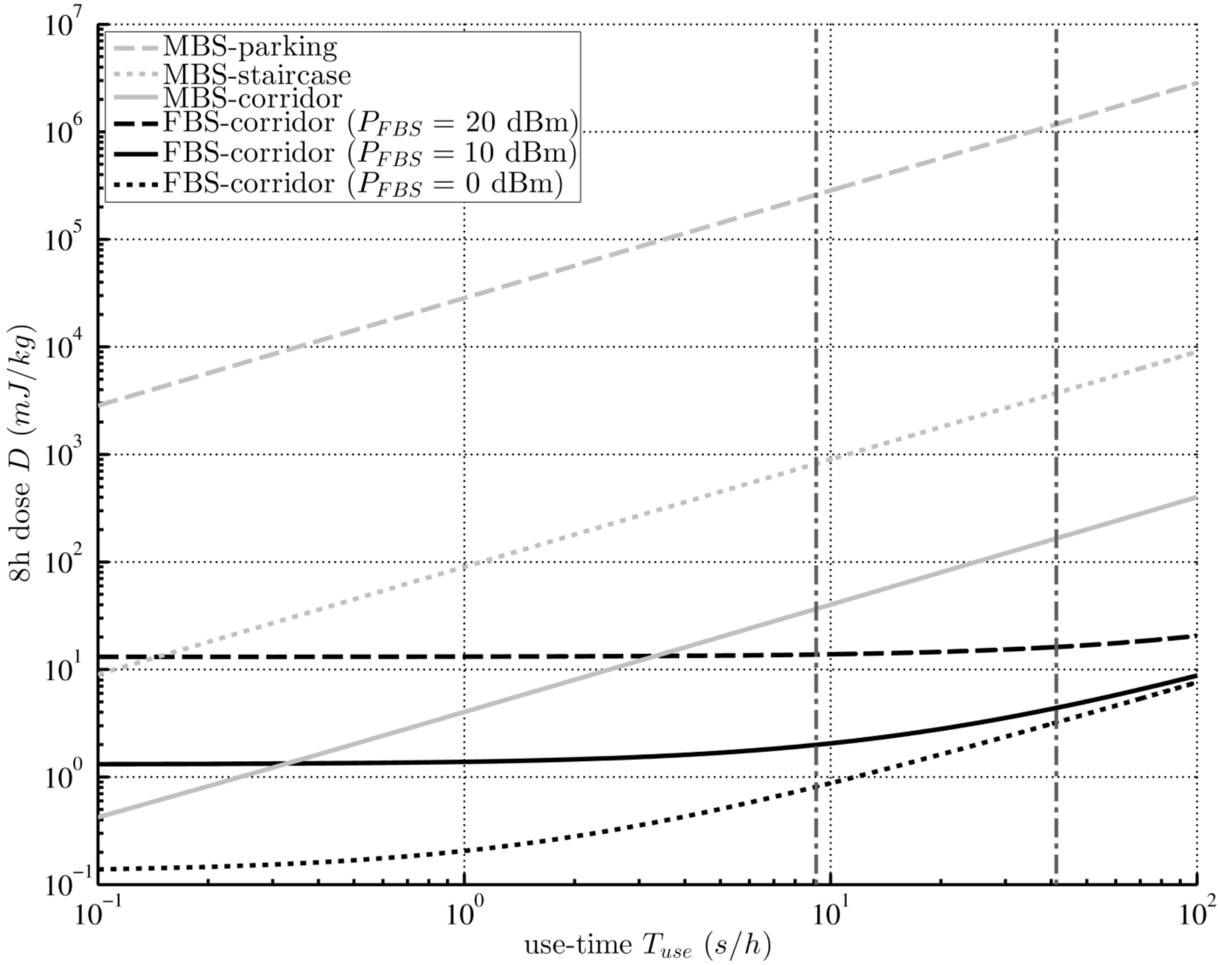
−50
−60
−70
−80
−90
0
10
20
30
40
50
60
70
measured power (dBm)
distance from FBS (m)
TX MBS
TX FBS
RSSI FBS
RSSI MBS

Figure 2



SA meas.
MP meas.
Calibrated MP meas.
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
power density (W/m^2)
0
2
4
6
8
10
12
14
16
18
distance from FBS (m)

Figure 3



MBS-parking
MBS-staircase
MBS-corridor
FBS-corridor (P_{FBS} = 20 dBm)
FBS-corridor (P_{FBS} = 10 dBm)
FBS-corridor (P_{FBS} = 0 dBm)
8h dose D (mJ/kg)
use-time T_{use} (s/h)
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-1}
10^{0}
10^{1}
10^{2}

Figure 4