Exposure Assessment in Heterogeneous Networks Accounting for up- and Downlinks

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Abstract. EMF exposure of people induced by both base station antennas and mobile terminal devices, in a heterogeneous network environment, in a given area, is addressed in this paper. The Specific Absorption Rate (SAR) and the Exposure Index (EI) are used to evaluate exposure, which takes multiple systems, users, postures, and usage profiles into account, among other aspects. One analyses the exposure in heterogeneous networks, consisting of GSM, UTMS, LTE and WLAN systems, for multiple usage scenarios. By using full systems simulations and exposure models, one estimates the EI for several conditions. The use of power control has a major impact on the SAR a person is exposed to. It is verified that, for the scenario under analysis, the uplink power of users' own terminal contributes to more than 90% to the overall SAR.

Keywords: EMF population exposure · Exposure Index · Simulation · Heterogeneous networks · Up- and downlinks

1 Introduction

Exposure induced by electromagnetic fields (EMF) emitted by wireless telecommunication systems is limited by threshold reference values recommended by international bodies, as ICNIRP [1]. Existing metrics to evaluate EMF exposure are well adapted to check the compliance with limits, but not at all to evaluate a global exposure of a population. Previous studies on this matter usually only look into a specific system, or to a specific mechanism that allows one to reduce exposure [2, 3]. Other studies analyse heterogeneous networks, but usually looking at the effect of adding small cells [4], or by using different allocation or routing strategies [5]. In the context of concern about possible health effects of EMF, the LEXNET project [6] (co-funded by the European Commission, under Framework Programme 7), started in November 2012 in response to this demand.

The strategic goal of LEXNET is to take the public concern on EMF possible health effects into account, and to improve the acceptability of existing and future wireless systems, through low exposure systems, without compromising the user's perceived Quality of Experience. One of the objectives of LEXNET was to define a new metric to evaluate the exposure of a population induced by a given wireless telecommunication network. The so-called Exposure Index (EI) [7] evaluates simultaneously the contributions of personal devices (e.g., mobile phones) and of networks' infrastructures (e.g., base station antennas) to the global exposure of users.

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To the best of our knowledge, this is the first paper to address and quantify this exposure from heterogeneous wireless communication systems using LEXNET's EI model. By using this approach, initial simulations were made to estimate global exposure on heterogeneous networks (GSM, UTMS, LTE and IEEE 802.11 g-WiFi systems), considering different scenarios, varying usage, mobility, number of users, etc. Afterwards, the EI was estimated for the considered systems and given scenarios. This enabled to have a better understanding of the overall exposure in heterogeneous networks, allowing one to know the exposure impact of the different considered systems, and for different users' behaviours.

Following this introduction, the EI model of the LEXNET project is described in Sect. 2. The simulation scenario is detailed in Sect. 3, followed by the analysis of simulation results in Sect. 4. Conclusions are drawn in Sect. 5.

2 Exposure Index Model

The model proposed to evaluate the EI of users in a given area with several communication systems is based on the work carried out in the LEXNET project [7–10] and is summarised here for clarity. The model divides the EI into down- and uplink components:

$$EI = EI^{\mathrm{DL}} + EI^{\mathrm{UL}} \quad [\mathrm{J/kg}] \tag{1}$$

where:

- EI^{DL} is the total downlink EI for all communication systems,
- EI^{UL} is the total uplink EI, coming from the devices in the proximity of the user.

The downlink EI exists independent of whether the user has an active connection, or even carries a communication system, i.e., it merely exists due to the presence of base stations. The total downlink EI is the sum of the EI components for each system, each one depending on the distance of the user to the base station, and the duration of the stay of the user inside the scenario.

The downlink EI_s^{DL} for a single system is given by

$$EI_S^{DL}(r_s, t, f_s) = P_{\mathrm{tx}} G_{\mathrm{tx}} \left(\frac{4\pi r_s f_s}{c}\right) t d_{f_s}^{DL} \tag{2}$$

where:

- P_{tx} is the transmission power [W],
- G_{tx} is the antenna gain,
- c is the speed of light in vacuum [m/s];
- r_s is the distance to the base station of system s [m];
- f_s is the carrier frequency of the used communication system s [Hz];
- t is the duration of the connection [s];
- $d_{f_s}^{DL}$ is the normalised Specific Absorption Rate (SAR) for the downlink [kg^{-1}].

Power control is not considered for the downlink. Since a single user cannot control the total downlink power of the base station, a worst case transmission power is assumed. The used frequencies for the various communication systems are given in Table 1. Although these communications systems can operate in a variety of frequency bands, the listed frequencies were used, because they coincide with the studied normalised SAR values within LEXNET. The normalised SAR for the downlink is given in Table 2.

Table 1. Frequency, maximum transmission power and antenna gain for the simulated systems.

	f_s [MHz]	P_{tx} [W]	G_{tx} [dBi]
GSM	1 800	40.0	0
UMTS	1 940	40.0	14
LTE	2 600	40.0	14
WLAN	2 400	00.1	0

Table 2. Normalised SAR for the different communication systems.

	Normalised SAR [kg^{-1}]	
	Downlink	Uplink
GSM (1 800 MHz)	0.0043	0.0053
UMTS (1 940 MHz)	0.0043	0.0053
LTE (2 600 MHz)	0.0039	0.0053
WLAN (2 400 MHz)	0.0053	

The total downlink EI, for a total of S systems, is then given by:

$$EI^{DL}(t) = \sum\nolimits_{s=1}^{S} EI_{S_n}^{DL}(r_s, t, f_s) \tag{3}$$

where:

- $EI_{s_n}^{DL}(\ldots)$ is the downlink EI for system n.

Unlike the downlink, the EI of the uplink depends solely on the active connections of the user with system S. The distance to the communication device is taken into account by the normalised SAR value. The uplink EI for a given system, EI_s^{UL}, is given by

$$EI_s^{UL}(t) = P_{tx} A_{s,u} d_{fs}^{UL} c \tag{4}$$

where:

- $A_{s,u}$ is the activity factor, depending on the users' activity and the used system, assumed to be 1 in here.
- $d_{f_s}^{UL}$ is the uplink normalised SAR [kg^{-1}] for the different frequencies, given in Table 2.

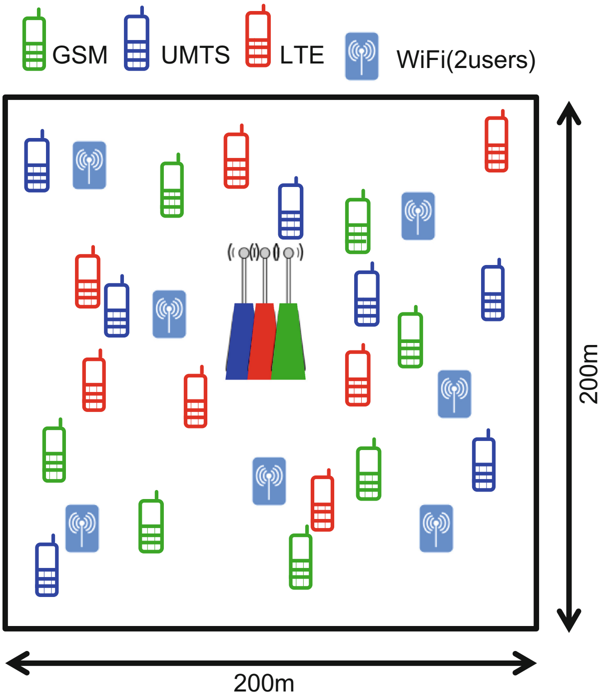


Fig. 1. Simulated scenario

3 Simulations and Scenarios

The scenarios were simulated using Riverbed Modeler [11], and show a macro-cell approach [12], with a 200 m side square area, where there are GSM, UMTS and LTE base-stations collocated at the centre of the cell, see Fig. 1. Power control is considered only for GSM and UMTS. The GSM base station is omni-directorial, whereas, the UMTS and LTE ones are tri-sectorised. The cell also contains a number of WLAN access points, randomly positioned within the cell. Users are also randomly positioned within the cell. The receive power values at the user terminal is used for downlink simulations. For uplink measurements, the transmit power is measured at 5 cm distance from the terminal, which roughly corresponds to the distance of a phone to a person. All users are outdoors, and only a single cell, albeit sectorised, is considered.

The considered reference scenario is composed of the four considered systems, with 7 users per cellular system, and 7 APs with 2 users each. As for the service, GSM users are using voice, while the rest of the users from the other systems are using P2P. It was decided to focus on the worst-case approach when designing and configuring the scenario: although the area under study is small, it is considered to be a macro-cell (thus, larger BS transmission power), the used propagation model being free space loss only.

Based on the reference scenario, several variations were defined to analyse specific scenarios:

- user's movement (pedestrian speed, without leaving the area under study);
- different types of traffic (FTP, P2P with heavier load, video conferencing) for all users except GSM ones who are always just doing voice;
- clustering of the cellular users with different distances to the bases stations (10, 50, 100, 200, and 500 m);
- increase the number of users of the cellular systems (to the double, triple, and quadruple of the reference situation).

The LEXNET *EI*-model was implemented in Octave, using reference values from the aforementioned simulations.

4 Simulation Results

This section evaluates the results of various scenarios and simulations. First the transmission powers of both down- and uplink are analysed, since the position of a user with respect to the base station and other users' has a direct impact to the EI. Secondly, the distribution of the EI of the different systems is evaluated, to give insights into the impact of these distances to the EI. Lastly, the EI of a single user is simulated for 1 h periods, to quantify the exposure a user can expect.

4.1 Received Power Simulations

The EI is highly dependent on the transmission powers, see Eqs. (2) and (4), therefore these values were obtained first. The results are the power values for both the down- and uplinks for each of the users, in each of the systems. In Table 3, the results from the reference scenario are presented, including the standard deviation. The results from all the users of a given system are averaged so that one can compare the "average exposure" among systems in both links.

Table 3. Received power for the different communication systems.

	Received power			
	Downlink		Uplink	
	Mean [dBm]	StdDev [dB]	Mean [dBm]	StdDev [dB]
GSM	−25.4	0.00	9.3	0.00
UMTS	−96.2	0.54	−48.4	0.59
LTE	−37.3	0.87	12.9	2.18
WLAN	−54.9	5.22	−40.1	23.35

As it can be seen, UMTS has much lower exposure values compared to other cellular systems. This is easily explained, since in our simulations UMTS uses advanced power control in the uplink, and there is a reduced number of users/load in the considered reference scenario. For LTE and GSM, the values are several orders of magnitude higher, but nevertheless, the power values are quite low, due to the relative small scenario, thus, all users being at a relatively short distance from the base stations. As for WLAN, power values are quite low in both up- and downlinks.

As for the cellular systems, the standard deviation is quite low as expected: there is no movement on the reference scenario, and thus, the transmitted power variation is also quite low. The standard deviation of WLAN is quite high, which can be explained by the reduced number of terminals (2 per AP) used in the simulations for WLAN users, thus, leading to higher variability between results.

There was also a variation on the type of service being considered, and it was seen that independently of the type of service used as a traffic load, the received powers do not show any appreciable variation, as it can be seen in Fig. 2. This indicates that the type of service does not yield a great influence on the received powers.

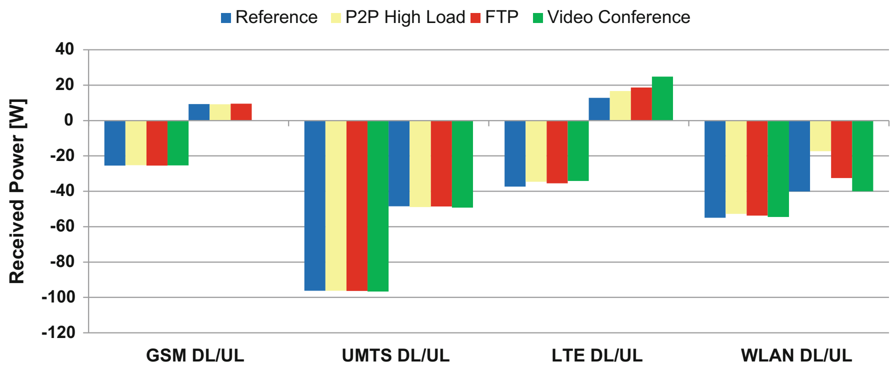


Fig. 2. Comparison of the received signal powers for different services.

The next step was to look at the impact of clustering, and of the distance from the users to the base station, the results being presented in Fig. 3. Simulations were performed with users clustered at distances of 10, 50, 100, 200 and 500 m from the base stations. There are no big changes in the results, but one can see the effects of power control (or lack thereof) on the received and transmitted power of the various systems under consideration.

In Fig. 4, the results are shown for the received powers when the number of users (or the load) increases. This was done with an increase by a factor of 2, 3 and 4 on the number of users, compared to the reference scenario.

UMTS power values, as expected, are very dependent on the load, but even so, it continues to be the system with the lower exposure values. As for the other systems, the variation is negligible among the different scenarios.

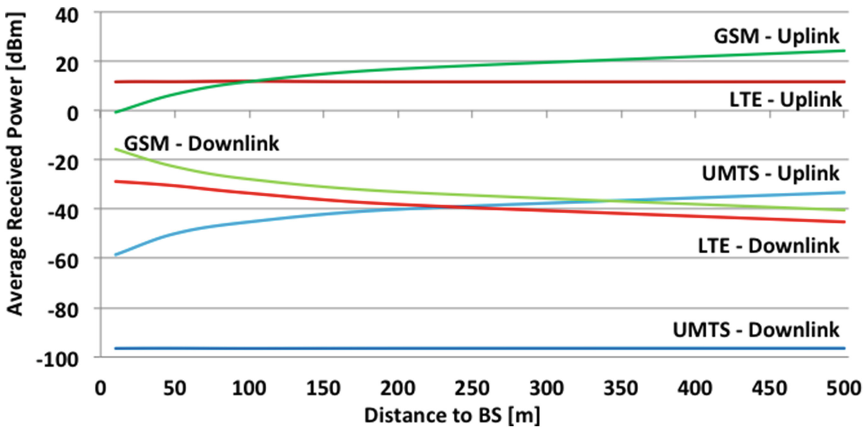


Fig. 3. Comparison of the received signal powers at the users' location of the systems for different distances to the BS

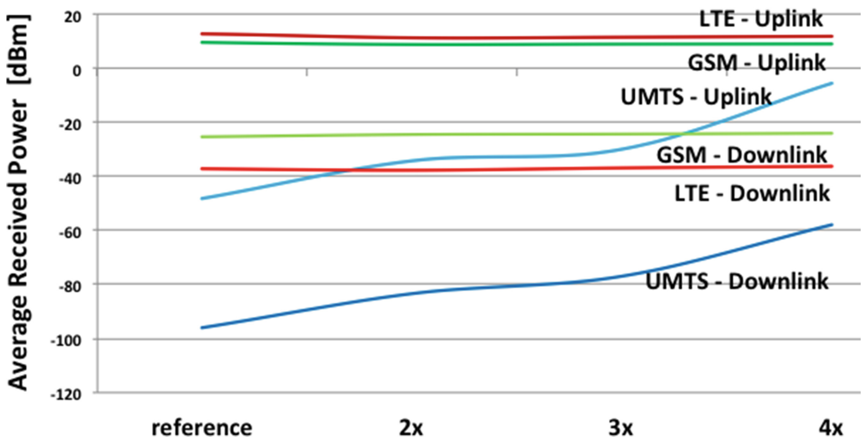
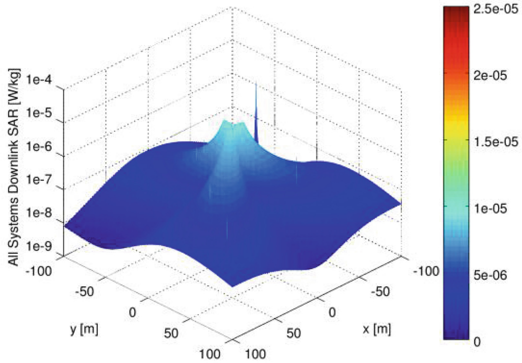


Fig. 4. Received signal powers at the users' location for user densities

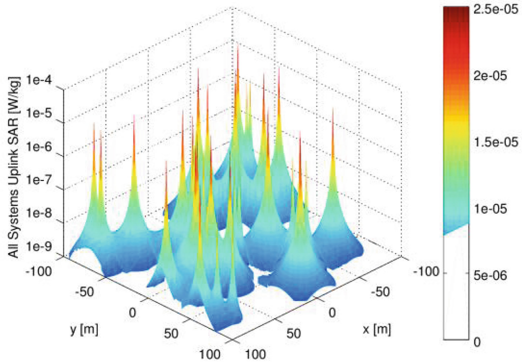
4.2 SAR Distribution Simulations

In this section, the SAR was simulated for the down- and uplinks of each simulated systems, for the same considered scenario. The results for all systems combined are shown in Fig. 5. The SAR values from the downlink transmission are given in Fig. 5a, the SAR values from the uplink transmissions in Fig. 5b, and the combined down- and uplink SAR values in Fig. 5c.

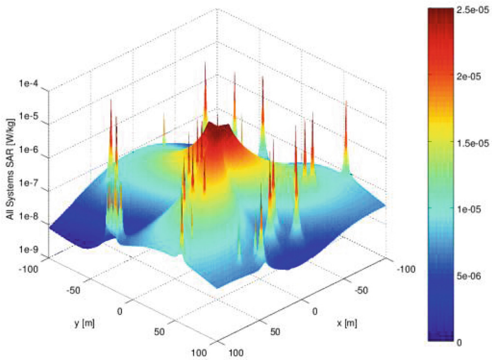
For UMTS, LTE and GSM, an exclusion zone of 10 m around the base-station is considered. The closest distance to the communication device of any system is 10 cm. Both up- and downlinks of WLAN are considered with a 10 cm exclusion zone. These exclusion zones are just for representation purposes, and do not interfere with the



a) Downlink SAR.



b) Uplink SAR.



c) Combined Downlink and Uplink SAR.

Fig. 5. Combined UMTS, LTE, GSM and WLAN SAR Distribution in a single cell

results. The effect of the exclusion zones around the base-stations can be recognised by flattened peaks of the SAR around the base-station, i.e., at coordinates (0, 0).

Each WLAN AP has 2 active users in its vicinity as it has been considered on the system level simulations, and this is easily recognisable in Fig. 5c, as there are some clusters of three peaks closely together.

In all simulations, the results are well below the limit of 2 W/kg (head) and the maximum average of 0.8 W/kg (complete body) as defined by ICNIRP's recommendations [1].

4.3 Exposure Index Simulations

The total cumulative SAR for a single user without mobile terminal is simulated and averaged over 1000 runs for a cell with four communication systems, with the same transmission characteristics as presented in Table 1. Three different traffic levels are simulated, i.e., low, medium and high. The low traffic level is the same level as the standard scenario, i.e., 7 active users for UMTS, 7 active users for LTE, 7 active users for GSM and 2 APs with 7 active users each. In the medium traffic scenario, the number of active users is increased to 14 for each of the cellular systems, and in the high traffic scenario the number is increased to 28.

The user follows a random-walk with a constant speed of 4 m/s. The user is bounced back from the outer areas of the cell and keeps on moving during the entire simulation. The user position is evaluated every second for a period of 1 h. The results for these simulations are given in Table 4. Due to the fast-decay of the transmitted powers with distance; the increase in active users does not have a significant impact in the observed cumulative SAR.

Table 4. Exposure index simulations for different user densities for a user without a mobile terminal.

	Exposure index [mJ/kg/h]		
	Mean	Max	StdDev
Low (7 active users)	0.76	5.17	0.83
Medium (14 active users)	0.81	5.44	0.84
High (28 active users)	0.76	5.35	0.76

The results from Table 5 do not include the radiation from the users' own mobile terminal. Assuming a sufficient number of active users in the cell, such that the radiation of the users' mobile is independent of the exposure from all other radiators, the component of the radiation perceived from the own terminal can simply be added to the already obtained values.

Also, the calculations were done considering perfect power control for all systems and using a noise margin for the receiver of −120 dBm and a receiver margin of 30 dB. Both LTE and UMTS use directional base station antennas with a maximum gain of

Table 5. Exposure index of the different systems.

	Exposure index [mJ/kg/h]		
	Mean	Max	StdDev
GSM	29.12	62.47	11.16
UMTS	07.77	35.90	06.08
LTE	13.56	64.48	10.92

14 dB and no antenna gain at the mobile terminal. The results in Table 5 are the average value, maximum and standard deviation for 1 000 random walk patterns. Since the added value is purely dependent of the users' mobile, the number of active users in the cell does not have any influence.

It is worth noting that although the maximum values are a factor of 3 to 5 times higher than the average value, they are still well below the legal limits. UMTS shows the lowest EI, followed by LTE and then GSM. WLAN was not considered, as it is not reasonable to expect WLAN coverage over the entire cell-range, which would lead to underestimated results.

In Table 6, the total Exposure Index (down- and uplinks) is given for the different systems, as well as the relative components for the down- and the uplinks.

Table 6. Absolute and relative exposure index of the different systems.

	Exposure index		
	Total [mJ/kg/h]	Downlink [%]	Uplink [%]
GSM	29.88	2.5	97.5
UMTS	08.53	8.9	91.1
LTE	13.56	5.3	94.7

As expected, the radiating power from ones' own mobile terminal is responsible for over 90 % of the SAR on the human body.

5 Conclusions

The goal of the LEXNET project is to take into account the public concern on possible health effects of electromagnetic fields and to improve the acceptability of existing and future wireless systems through low exposure systems without compromising the user's perceived quality. Under this flag, this paper investigates the Exposure Index for the down- and uplinks, as experienced by users in a single cell.

The scenario under evaluation is a single macro-cellular scenario, with GSM, UMTS, LTE and WLAN systems. GSM, UMTS and LTE BSs are co-located at the centre of the cell, where UMTS and LTE are tri-sectorised. Simulations, using Riverbed Modeler, were made for different mobility patterns, services, users and user clustering. The base scenario (no mobility, 7 users for each system in a 200 × 200 m^2 area) shows that UMTS has a much lower exposure value, compared to the other systems. Increasing the number of users shows the largest impact in UMTS, as it is based on Code Division Multiple Access. The type of service does not have a large impact on the results, as in all cases the system has a decent traffic load.

Exposure Index simulations, implemented in Octave, show the SAR distribution for each system in the down- and uplinks, and a combined SAR distribution for all systems. From these figures one can extract that the peaks for the SAR follow the user distribution.

Simulations showed that power control has a major impact on the cumulative SAR a person is exposed to. More interestingly, simulations have also shown that the uplink from the users' terminal is responsible for over 90 % of the exposed SAR, when the user is making a call or using a data connection. Also, the user has little control over the downlink contribution to the SAR, as it depends on all the users in the cell. Future communications systems need to optimise the uplink power, as it is the main component of the SAR exposure of users. Denser networks can lead to a decrease in SAR, as the user is closer to the base station, needing less power to transmit.

Although many simulations have been run, the scenario (200 × 200 m^2) does not vary. It would be interesting to analyse the EI for more realistic scenarios and path-loss models. More recent releases of LTE have added power control, and this may have a severe (positive) impact on the LTE results. Future work will also include the received powers of base stations in neighbouring cells and of multiple operators to better match a realistic environment.

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