RF-EMF exposure induced by mobile phones operating in LTE small cells in two different urban cities

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Abstract-

With the huge growth in data traffic, the densification of the macro cell (MC) layer with low-powered small cell (SC) base stations (resulting in a heterogeneous network) will improve network performances in terms of radio coverage and capacity. However, this may influence the human exposure to radio-frequency electromagnetic fields (RF-EMFs). Through measurement campaigns in two different urban cities (in France and the Netherlands), the authors characterized the RF-EMF exposure induced by LTE (Long Term Evolution) MC and SC networks, while considering radio emissions from both base stations (downlink or DL) and user equipment (uplink or UL). For an internet data usage and with respect to an MC connection, results showed that an SC connection may increase the DL exposure while decreasing the UL exposure (with a factor of 5 to 17), mainly due to the lower mobile phone emitted power and depending on whether the throughput is limited or not. Furthermore, the city with a dense network is characterized by low UL exposure and high DL exposure.

Keywords- electromagnetic field, heterogeneous network, human exposure, radio frequency, small cell.

1. Introduction

With the huge growth in data traffic [1], network operators aim to overcome fundamental challenges related to radio coverage and capacity. Hence, they will adopt new network architectures such as heterogeneous networks (HetNets) where small cell (SC) base stations will be densely deployed within macro cells (MCs), providing also a smooth migration path towards the fifth generation (5G). In contrast to MCs, SCs are low-powered, low-height base stations with coverage ranging from 10 meters up to few kilometers [2,3]. A dense deployment of SCs, in indoor as well as in outdoor environments, would provide better propagation conditions for connected user equipment (UE) (e.g., mobile phones, tablets, and emerging virtual reality terminals) and therefore, high-speed connectivity.

While offering better quality of service, the deployment of SCs may result in added public concern about human exposure to radiofrequency (RF) electromagnetic fields (EMFs). RF-EMF exposure can be subdivided in two components, generally depending on the source. On the one hand, permanent downlink (DL) exposure results from signals emitted by base station antennas. On the other hand, uplink (UL) exposure induced by UE, though usually sporadic, is well known to be the most critical exposure component, due to its close proximity to human body [4]. As both DL and UL exposures are affected by the propagation channel conditions, and thus through transmit power control algorithms [5,6], the exposure induced in SC networks will obviously differ from the one induced in MC networks owing to the difference in network architecture. Therefore, it is crucial to characterize RF-EMF exposure induced in a HetNet configuration and to check compliance with international EMF safety limits [7]. Such a characterization is useful for future epidemiological studies.

While RF-EMF exposure induced in either second generation (2G) or third generation (3G) SC networks was addressed in [8-11], rare works considered exposure induced in fourth generation long-term evolution (4G-LTE) HetNets, even though LTE traffic accounted for 69% of mobile traffic in 2016 [1]. Indeed, EMF exposure induced in LTE HetNets has been assessed using simulations in [12] and through a measurement campaign in an urban environment in [13], though in the latter, only the UL exposure in one specific environment was considered. However, both UL and DL need to be characterized in diverse environments to assess the real exposure burden, thus considering larger measurement campaigns. Therefore, the present work aims to assess in-situ human RF-EMF exposure (both UL and DL) induced in LTE HetNets in two different urban environments (i.e., in Annecy, France, and in Amsterdam, the Netherlands) through measurement campaigns. The cities differ in their population densities as well as in the characteristics of the present HetNets, including base station densities. The analysis of the human exposure to RF-EMF relies in this work on a comparison between SC and MC connections as well as between the two different cities, while considering an internet data service (i.e., file transfer protocol or FTP).

2. Materials & Methods

2.1. Measurement parameters

RF-EMF exposure is usually assessed in terms of the specific absorption rate (SAR), which is the amount of EMF absorbed per mass of tissue. Regardless of the dependence on the frequency band, SAR is proportional to the total power received by the human body. In the LTE mode, the UE measures both RSRP (Reference Signal Received Power) and RSSI (Received Strength Signal Indicator) [14]. The RSRP is the average narrowband received power of the resource elements that carry cell-specific reference signals, whereas the RSSI is the wideband received power including interferences from other cells, computed solely over the 'UE allocated bandwidth'. Consequently, the total received power over the whole bandwidth is not proportional to the reported RSSI, though it could be proportional to the RSRP. Accordingly, in the following analysis the RSRP is considered as a measure of the DL exposure, suitable for fair comparisons, even though it does not account for noise and interferences.

In the case of UL exposure, the SAR also depends on the posture since accordingly the signals emitted by UE may experience different attenuations. More clearly, this happens while using internet data services where the mobile phone is held in front of the human body, which is very different compared to voice services where the mobile phone is held directly to the ear. However, assuming the same posture for the same internet usage, the UE transmit power (i.e. UE TX power) may be used to perform a fair comparison and analysis in terms of RF-EMF exposure. While the DL exposure is permanent but not constantly at the same level, the UL exposure depends on the duration of the usage. Such duration may be inversely proportional to the data throughput, especially in the case of internet data services. Hence, both the UE TX power and throughput are crucial parameters in the characterization of the UL exposure.

Furthermore, all these measured parameters may be involved in the computation of the exposure index [4,8,9,15] which quantifies the global exposure of a population considering a certain realistic scenario over space and time. The exposure index takes into account many more variables and parameters. However, in the present work, only the aforementioned three parameters are considered, in order to perform fair comparisons and understand the impact of both the environment and the network architecture on the RF-EMF exposure.

2.2. Measurement equipment

The LTE network parameters used for the analysis were recorded using two different android-based drive test solutions, i.e. Viavi JDSU solution [16], installed on a Samsung Galaxy S4, and Azenqos (AZQ) [17], developed by Freewill FX Company Limited and installed on an LG Nexus 5. During the measurements, both UE were locked to operate over the LTE band only and programmed to automatically upload files through FTP, in order to simulate UL exposure.

There are some differences between JDSU and AZQ applications. While the sampling period of JDSU is not constant, that of AZQ is (i.e., 100 ms), where each sample is the average value over the sampling period. For the sake of fair comparison, the data is post-processed by computing average values per second. Moreover, JDSU provides the TX power over the physical channel dedicated for data exchange (PUSCH, or physical up-link shared channel) while AZQ provides the total TX power. Nevertheless, in the following these powers are denoted as the “UE TX power”. Furthermore, the access to the FTP server was unlimited when using JDSU, but limited when using AZQ. This resulted in different real-life use cases according to the users’ mobile phone plan.

2.3. Measurement description

The measurement campaigns were carried out in Annecy (France) and Amsterdam (the Netherlands) in January 2017 and September 2016, respectively. These two cities are characterized by different geographical areas as well as different population densities (i.e., 1900 people per km² for Annecy, and 4908 people per km² for Amsterdam). It is important to realize that in Amsterdam, in contrast to Annecy, SCs were densely deployed throughout the city center. Furthermore, the present SCs were equipped with directional antennas, and deployed on urban furniture such as bus stations and advertisement panels; at a height of about 3 m. Illustrative information about the SC deployment and the measurement environment is given in Fig. *1*.

In Annecy, France, measurements were performed at two SC sites (Figure 1a), located at an MC edge. At one SC site, the base station radiates in a single direction at a power of 4 W. At the other, the base station radiates in two different directions at a power of 0.91 W. At each SC site, an experimenter walked around in its vicinity, following a specific path four times, using either JDSU or AZQ and with the SCs turned either ‘on’ or ‘off’ (which resulted in an SC and an MC scenario). Such walking measurements allowed covering different separation distances between the mobile phone and the connected base station, up to 100 m (corresponding to the SC coverage), reaching different shadowing conditions and thereby covering different propagation conditions. The size of the FTP files used in these measurements was 100 MB.

In Amsterdam, the Netherlands, measurements were performed at six sites throughout the city. At the center of each site was a bus stop on which either one or two SC base stations were installed (Fig. *1*b). No information is available on the radiation patterns and output powers of the SCs. Two experimenters walked around in the vicinity of the center bus stop, with a maximum separation of about 50 m, with either AZQ or JDSU equipped smartphones, sequentially uploading 10 MB and 100 MB files to an FTP server. Again, this allowed covering different shadowing and propagation conditions.

During the measurements, it also became clear that, at two sites, the present SC base stations were not active. In these cases, the phones were connected to nearby MCs. Of the remaining sites, two had one SC base station, and two had two SC base stations. In the latter case, the phone’s connection switched between the two base stations – generally the closest to the smartphone.

3. Results

The LTE network parameters collected during the measurements were statistically analyzed by computing their cumulative distribution functions (CDFs) and summarized by evaluating the linear average, the median, the 95-th percentile, and the standard deviation (σ). **For both the UE TX power and the RSRP, the average is computed using the absolute values (in mW) and then expressed in dBm, while the standard deviation is computed directly in dBm.**

3.1. Correlation between TX power and RSRP

Fig. *2* shows the variation of the UE TX power with the RSRP, collected with AZQ in both SC and MC scenarios and in each city. As expected from [5], the UE TX power is roughly inversely proportional to the RSRP. This is explained by the fact that the RSRP, as it is inversely proportional to the path loss (PL), is exploited by the transmit power control algorithm in order to determine the UE TX power [6]. Accordingly, both high RSRP values and low TX powers correspond to good propagation conditions, where the UE is close to a base station or in line-of-sight (LOS) of (one of) its antenna(s). In contrast, low RSRP and high TX power values correspond to bad propagation conditions in which the UE could be very far from the base station.

3.2. RSRP statistics

The CDFs of the RSRP for both cities are shown in Figure 3, while comparing SC and MC scenarios. The main statistical characteristics are summarized in Table 1 for both JDSU and AZQ.

For each city and drive test tool, in general, higher RSRP values were measured when the UE was connected to an SC. For example, in Annecy, the RSRP varied between -120 dBm and -80 dBm in the MC scenarios (i.e., “SC off”) compared to -120 dBm and -65 dBm with the SCs turned on. Obviously, this is due to the low height of the SC antennas that allowed the UEs to be moved closer to the base stations and thereby improve the propagation conditions. However, in both SC and MC scenarios, similar bad propagation conditions (and hence low RSRP values) are possible in regions far from or in non-LOS (NLOS) of the base stations the UE is connected to.

Furthermore, for each scenario, the RSRP reached lower values in Annecy than in Amsterdam. Indeed, the LTE network in Annecy was not densely populated with either MC or SC base stations, yielding large coverage ranges (about 100 m for SCs, corresponding to the measurement distances around each SC site). This is in contrast with Amsterdam where the density of the network yields smaller coverage ranges (about 50 m for SCs, corresponding again to the measurement distances). Moreover, in Annecy, various parts of the measurement walks were in NLOS of the base stations, in the case of SC connection, while in the case of MC connection, the measurements was very far from MC base stations.

3.3. UE TX power

The statistics of the UE TX power are shown in Figure 4 and summarized in Table 2. For the MC scenario, average TX powers recorded by JDSU and AZQ were respectively 17.91 dBm and 16.10 dBm in Annecy, and 19.44 dBm and 17.69 dBm in Amsterdam. Lower TX powers were found in the SC scenarios where, in Annecy, the average was 14.49 dBm (JDSU) and 11.20 dBm (AZQ). Moreover, in the SC scenario, Amsterdam was characterized by a lower UE TX power (median: -14.84 dBm) than Annecy (median: 1.31 dBm). Indeed, as already seen, the TX power is heavily correlated to the RSRP.

Furthermore, the TX powers recorded with AZQ were generally lower than those recorded with JDSU. This can be attributed to the fact that AZQ accounts for the total TX power, including both data and control signals, while JDSU considers only the signals carrying data. The TX power within the control signals is actually very low, since it occurs over narrowband signals, and these signals are transmitted either independently or with the signals carrying data. The regular sampling of AZQ resulted in a lot of samples of just the power emitted in the control signal, lowering the average TX power.

3.4. Throughput

Figure 5 shows the CDFs of the normalized throughput and Table 3 lists the statistical summary. As the access to the FTP server was limited with AZQ, throughputs recorded with it were lower than those recorded with JDSU, for which unlimited bandwidth was available. Consequently, it is not very reliable to perform a throughput analysis for the different scenarios using AZQ, even though it represents a realistic use case, where the limited throughput **may be due** to either the application (as here the FTP over AZQ) or the (prepaid) data plan (e.g., after reaching a certain percentage of the total purchased data).

Using AZQ, no significant difference was noted in throughput between MC and SC scenarios in Amsterdam, while an enhanced throughput was observed with an SC in Annecy. Indeed, with the SC turned off in Annecy, the throughput was very low and did not reach the maximum limited value (assigned to the user’s mobile phone plan), in contrast with Amsterdam.

The advantage of SC deployment is more clearly seen with JDSU, where the (unlimited) throughput measured in the SC scenarios reached much higher values than those in MC scenarios, both in Amsterdam and in Annecy. Indeed, owing to data offloading in HetNets, more resources are available for each UE. **Thus, better quality of service is provided.**

4. Discussion

In general, SC LTE connection scenarios are characterized by lower TX powers, higher RSRP values, and higher (or equal) throughputs, compared to MC scenarios (Figure 6a, b, c). From an RF-EMF exposure point of view, this is interpreted as an increase in the DL exposure and a decrease in the UL exposure in the SC scenarios. Indeed, while DL exposure is proportional to the RSRP, UL exposure is proportional to the UE TX power and inversely proportional to the throughput. Hence, the UL exposure can be compared by computing a ratio between the TX power and the throughput and consequently the SC to MC UL exposure ratio can be assessed, as shown in Figure 6d. Unfortunately, due to the inherent differences between the drive test solutions JDSU and AZQ, their respective measurements could not be aggregated. However, the conclusions using both data sets are consistent.

If one considers, for example, the measurements carried out in Annecy with JDSU, Figure 6 shows that, compared to the MC scenario, in the SC scenario the RSRP (and thus the DL exposure) was on average a factor of 9.44 higher. The TX power was on average a factor of 2.17 lower and the throughput a factor of 4.78 higher. This results in an average decrease of the UL exposure by a factor of 10. However, using AZQ, limited the UL exposure reduction factor to 5, due to its throughput limitation. Furthermore, it is noted that, in Annecy, the exposure comparison between MC and SC scenarios reveals the benefits brought by the SC since the same area was considered with the SC turned either on or off.

Figure 7 compares the results between Annecy and Amsterdam. By calculating the ratios of the UE TX powers, the RSRPs, and the throughputs measured in Annecy and Amsterdam (Figure 7a, b, c), as well as the resulting UL exposure ratios (Figure 7d), a comprehensive exposure comparison between the two cities was made.

Connected to an MC, the TX powers recorded in Annecy were lower than those recorded in Amsterdam by about 30% on average (Figure 7a). Moreover, using JDSU, the throughputs in Annecy were on average 60% lower than those recorded in Amsterdam (Figure 7b). From an UL exposure perspective, this meant a lower TX power during a longer exposure duration in Annecy, but finally a higher UL exposure, by 75% (a ratio of 1.75 for JDSU) or 47% (a ratio of 1.47 for AZQ) (Figure 7d). Furthermore, owing to the lower density of base stations (implying lower cell coverage), RSRPs in Annecy were much lower than those in Amsterdam, resulting in a lower DL exposure in the former (Figure 7c).

Regarding the SC connection, on the other hand, the TX powers in Annecy were higher than in Amsterdam, with an average factor of 4.03, owing to the larger separation distances. With JDSU, higher throughputs were recorded in Annecy (with a factor of about 1.2) while lower throughputs were recorded with AZQ (with a factor of about 0.9). Consequently, from UL exposure point of view, Annecy is characterized by higher UE TX powers while the exposure duration depends on the user's mobile phone plan. The Annecy to Amsterdam UL exposure ratio, as shown in Figure 7d, is 4.38 while using AZQ recorded throughput and 3.25 if the throughput recorded with JDSU is considered. This reveals that higher UL exposure occurs in Annecy, mainly owing to the large coverage of SCs.

5. Conclusions

In the present work the human exposure to RF-EMF in both MC and SC networks was characterized, in two different urban cities and while considering data usage service on different drive test solutions. With respect to the sole deployment of MCs, LTE SCs may increase the DL exposure (with a factor of 7 – 46), though their impact ultimately depends on the deployment density and potential proximity to passers-by. At the same time decreasing the UL exposure (with a factor of 5 – 17), which, in its turn, depends not only on the UE TX power, but also on the duration of the exposure. However, the duration of UE use may not always decrease when connected to a SC since it is inversely proportional to the throughput, which may be reduced or limited s(as was the case using AZQ) due to either the application (as here the FTP) or the (prepaid) data plan (e.g., after reaching a certain percentage of the total purchased data). Furthermore, a dense network such as in Amsterdam may imply small radio coverage and thereby low UL exposure and high DL exposure. The authors intend in future work to exploit the aforementioned parameters in order to assess the population global exposure through the evaluation of the exposure index.

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