On the Reduction in Specific Absorption Rate Using Uplink Power Adaptation in Heterogeneous Small-Cell Networks

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\textbf{Abstract}—Recent growth in wireless devices such as smart phones, tablet computers, ipads and other electronic devices made the use of radio frequency spectrum omnipresent. The widespread of wireless devices has raised health concerns due to the possible malign effects of electromagnetic radiations on the human body, and especially on the brain due to its proximity with the hand-held radio devices. These radiations are absorbed in the head while making phone calls and increase the health risks. The rate at which these radiations are absorbed in the head is referred to as specific absorption rate (SAR) and is dependent on the strength of the transmitted signals. This paper investigates a new design for future generations of wireless networks where low-power, low-cost and small-cell base stations are deployed to support the infrastructure of macrocell base stations. The resulting network is referred to as heterogeneous network (HetNet). HetNets are considered as a promising solution for situations when the mobile users have to adapt very fast their uplink transmit power over the fading channels. HetNet reduces the distance between the mobile users and the corresponding small-cell base stations. Therefore, the mobile users are no longer in need to transmit with maximum power to maintain the desired signal to interference noise ratio (SINR) and thereby the transmit power is reduced considerably especially when the mobile users are located far away form the desired base station, i.e., around the edge of the cell. Several simulations are provided to illustrate the reduction in the signal absorption rate (SAR) due to the uplink power adaptation. It is also shown that the other traditional gains such as spectral and energy efficiency of the system under consideration are significantly outperformed in comparison with the existing macrocell network.

\textbf{Index Terms}—Specific absorption rate; fast power control; heterogeneous networks; spectral and energy efficiency.

\section{I. INTRODUCTION}

The omnipresence of mobile devices increased the concern of people towards the potential harmful effects of the RF radiations on the human body. The electromagnetic radiations produced by mobile phones are classified by the International Agency for Research on Cancer (IARC) as possibly carcinogenic to humans \cite{IARC1}. Mobile phones are mostly used near the human head or brain and may present psychological and physiological implications, especially due to the heating effect of these radiations when phones are used for extended duration. Moreover, it was also found out that the transmitted radiations can modify the thyroid hormone levels, which are important for metabolism and temperature regulation in the body \cite{IARC2}.

Universally, the human body exposure to radio frequencies (RF) radiations from mobile devices is quantified using the Specific Absorption Rate (SAR), which is measured in watts per kilogram (W/kg). SAR is acknowledged as the global measure of exposure to electromagnetic radiations, and the corresponding numerical value is described in the product-manual of the mobile devices. Internationally, all base station (BS) and mobile device manufacturers are bound to follow certain guidelines to ensure a strict RF exposure limit (e.g., a maximum SAR value of 2 W/kg) set by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) for making the use of these devices safe \cite{ICNIRP1}. However, it is always highly desirable to further reduce the SAR of the mobile devices and thereby reduce the health risks involved due to the presence of the RF signals.

\subsection{A. Background Work}

There were many studies conducted to measure the effect of electromagnetic radiations on the human head tissues \cite{ICNIRP2, ICNIRP3}. In the study \cite{ICNIRP4}, the thermal effect of these radiations were noted, and it was determined that the absorption levels in skin and cerebrospinal fluid (CSF) tissues are more than the recommended safety limits while the induced temperature in the brain was insignificant to cause damage to the brain neurons. Usually, absorption increases with the rise of conductivities of tissues, and decline with the rise of relative permittivity of the tissues \cite{ICNIRP5}. This has caused a serious concern among the people regarding the adverse effects of electromagnetic radiations on the children’s brain due to their susceptibility to RF absorption because of their different conductivity and permittivity values. In \cite{ICNIRP6}, an effort has been made to simulate the electromagnetic radiation effects on children compared to adults. The findings of this research indicated that the RF absorption is in fact age dependent, and RF penetrates deep into the children’s brain as compared to the adults.

The SAR mainly depends upon two parameters, namely: (i) the distance between the mobile device and head, and (ii) the uplink transmit power of the mobile device. Mobile devices tend to use the minimum amount of energy to provide a connectivity in the presence of a good signal from the BS. The signal from a BS becomes weaker when the mobile is far away from the BS or it encounters obstructions like trees or buildings. This results in an increase in the transmit power of the mobile user to communicate with the respective BS.
Several ways to reduce the SAR have been proposed by the World Health Organization (WHO) such as the use of hands-free devices to keep the RF devices away from head, and by controlling the exposure by reducing the number and length of calls. WHO has also recommended to use the mobile phones in areas of considerably good reception, since such a scenario will allow the phone to transmit at reduced power. However, these measures are hard to implement as generally people have no idea about the location of the base stations (BS). Moreover, it is also very hard to avoid using mobile devices for extended duration as mobiles have gained the status of the sole communication medium in this modern era. Other efforts were also made to reduce the SAR by designing RF fields absorbing mobile phone covers and shielding mobile phones with copper [8] but these techniques significantly deter the quality of the calls. Therefore, WHO has raised concerns on its efficacy [1]. Electromagnetic Band Gap (EBG) Antennas [18], are also introduced to efficiently reduce the amount of radiations directed towards the head and hence, reducing the SAR. However, their design and implementation cost is much higher, resulting in a very few Handsets available that actually used this technology.

B. Heterogeneous Networks

Newly emerged heterogeneous networks (HetNets) offer a remarkable solution for the present wireless networks. Two straining issues are the requirement of high data-rate transmissions and the high energy efficiency in the future wireless networks. HetNets link together various user deployed low cost base stations (BSs) such as microcells, femtocells, and picocells, where the propagation distance between the transmitter and the receiver is reduced significantly. The mobile users are not required to transmit with the maximum power to achieve the desired signal to noise and interference ratio (SINR). Therefore, the SAR of the mobile devices can be reduced considerably since the absorption of electromagnetic emissions from mobile devices is fundamentally dependent on the transmit power of the device. However, the deployment of small-cell across the macrocell is a challenging problem and careful designing of HetNets is required to ensure that the mobile devices always transmit at the minimum possible power.

This paper proposes a network level remedy to reduce the RF absorption levels in the human head by exploiting the deployment of small cells in such a way that most of the mobile users per macrocell will transmit with the minimum power without compromising their link quality. This will not only reduce the amount of transmitted power from the hand-held devices but also increase the overall spectral and energy efficiency of the network. We consider that the small-cells are distributed uniformly across the macrocell such that the configuration is referred to as uniformly distributed cells (UDC) where the mobile users are adapting their uplink power intelligently to minimize the transmit power and improve the SAR of the mobile devices. In this context, we consider a simple human head model which consists of three layers: skin, bone and brain. The numerical value of the SAR was calculated corresponding to the uplink transmitted power of the mobile devices over the range of the distances between the hand-held devices and the human head. This study is done in order to emphasize the possible detrimental effects of radio signals on the human health.

The rest of the paper is organized as follows. Section II discusses the system model with emphasis on network layout and the bandwidth allocation strategy. In Section III, we discuss the uplink transmission design for HetNets. In Section IV, we present the SAR analysis based on the three layer human head model. Section V presents the performance analysis and simulation results of the system. An illustrative comparison with the macro-only networks based on power adaptation, SAR, spectral and energy efficiency is presented. Finally, conclusions are presented in Section VI.

II. SYSTEM MODEL

In this section, we explain the network layout and mobile user distribution across the macrocell in HetNets. We consider a two tier energy aware HetNets where the small-cell network complements the macrocell networks. The first tier of the considered HetNets comprises circular macrocells, each of radius $R_m$ [m], with a BS deployed at the center of the cell and equipped with an omnidirectional antenna. Each macrocell is assumed to have $H$ mobile users uniformly distributed over the region bounded by $R_0$ and $R_m$, where $R_0$ denotes the a minimum distance between the macrocell mobile user and its serving BS.

The second tier of the heterogeneous network comprises $N$ circular small-cells each of radius $R_s$ [m], with low-power low-cost user deployed small-cell base stations (BSBs) located at the center of each small-cell. We consider that the small-cells are distributed uniformly across the macrocell such that the number of small-cells per macrocell is given by

$$N = \left\{ \begin{array}{ll} \frac{A_m}{\pi R_m^2} & R_m > R_n \\ 0 & R_m \leq R_n, \end{array} \right.$$  \hspace{1cm} (1)

where $A_m = \pi R_m^2$ is the macrocell area, $A_n = \pi R_n^2$ is the small-cell area and the factor $0 < \mu \leq 1$ is referred to as the cell population factor (CPF), and which controls the number of small-cells per macrocell:

$$\mu = \begin{cases} 
0 & \text{off-load small-cells} \\
1 & \text{maximum number of small-cells per macrocell}. 
\end{cases}$$

The number of mobile users in each of the small-cell is calculated as $F = HA_m/N A_m$. Similarly, the number of remaining mobile users in macrocells is calculated as $L = H - NF$.

In the UDC configuration, $F$ out of $H$ mobile users are uniformly distributed over each of the $N$ small-cells, whereas the remaining mobile users ($L$) are uniformly distributed in the region bounded by $R_0$ and $R_m$. We consider the spectrum partition based on the proportion of the number of mobile users in the macrocell and the small-cells [9]. The bandwidth allocated to a macrocell is reused throughout the macrocell network at a distance $D' = R_0(R_m + R_n)$ [m], where $R_0$ represents the network traffic load. The total number of mobile users is distributed in each of the $N$ small-cells within a macrocell.

III. UPLINK TRANSMISSION DESIGN FOR HETNETS

The radio environment of a typical wireless cellular network is described by (i) distance dependent path-loss, (ii) shadowing, and (iii) multi path fading. In our analysis, we consider a two slope path-loss model for the macrocell and small-cell networks [10].

The received signal power from the mobile user at the respective BS can be expressed as

$$P_{rx}(r) = r^{-a}(1 + r/g)^{-\beta} P_{tx}(r) \zeta,$$  \hspace{1cm} (2)
where

- $P_{tx}(r)$ [W] denotes the average received power signal at the reference BS from the desired mobile user which is located at a distance $r$ from the same reference BS;
- $\zeta$ is the composite shadowing and fading component over the link between the mobile user and respective BS;
- $\alpha$ and $\beta$ are the basic and additional path loss exponents, respectively;
- $g = \frac{4h_c h_{tx}}{\lambda}$ [m] is the breakpoint of a path-loss curve which depends on the BS antenna height $h_{tx}$ [m], the antenna height of mobile device $h_c$ [m] and wavelength of the carrier frequency $\lambda$.
- $P_{tx}(r)$ [W] defines the mobile user uplink transmit power such that each of mobile users in the network adapts its transmit power according to the fast power control mechanism [11]–[14]:

$$P_{tx}(r) = \min \left( P_{max}, P_0 PL(r) \right).$$

- $P_{max}$ [W] is the maximum transmit power of each of the mobile users in HetNet;
- $PL(r)$ is the combined total path-loss\(^1\) for the uplink, which is expressed by using the two-slope path-loss model as

$$PL(r) = \frac{r^\alpha (1 + r/g) ^\beta}{\zeta}.$$  

- $P_0$ is the desired target signal to interference noise ratio (SINR).

Using (3) and (4), (2) can be expressed as

$$P_{tx}(r) = \begin{cases} P_{max}/PL(r) & P_{max} < P_0 PL(r) \\ P_0 & \text{otherwise.} \end{cases}$$

IV. SPECIFIC ABSORPTION RATE (SAR)

Generally, the expression of SAR over a sample material $(r)$ can be represented as:

$$SAR = \int_s \frac{\sigma(s)|E(s)|^2}{\rho(s)} ds,$$  

where
- $\sigma$ [S/m] is the electrical connectivity;
- $|E|$ [$\mu$V/m] is the root mean square (RMS) electric filed of the transmitting antenna;
- $\rho$ [kg/m]\(^3\)] is the density of the sample.

We have considered a simple human head model taken from [15] consisting of three layers, namely, skin, bone and brain to verify the SAR in human head. The electrical properties of these tissues at 900 MHz are depicted in the table bellow:

<table>
<thead>
<tr>
<th>Tissue</th>
<th>$\varepsilon_r$</th>
<th>$\sigma$(S/m)</th>
<th>$\rho$(kg/m(^3)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skin</td>
<td>39.5</td>
<td>0.69</td>
<td>1010</td>
</tr>
<tr>
<td>Bone</td>
<td>17.4</td>
<td>0.19</td>
<td>1810</td>
</tr>
<tr>
<td>Brain</td>
<td>45.8</td>
<td>0.76</td>
<td>1025</td>
</tr>
</tbody>
</table>

SAR can also be represented in the summation notation as:

$$SAR = \sum_{s=1}^{n} \frac{\sigma(s)|E(s)|^2}{\rho(s)}.$$  

\(^1\)Here, total path-loss includes path-loss, shadowing and fading, where the shadowing and path-loss can be estimated by the mobile users and the fading statistics can be transmitted by the BS using feedback to the mobile users.

For simplicity we have chosen a three layer model $n = 3$ for our simulations. However, some work has also considered models with more then three layers [5]. We have summed up the $\sigma/\rho$ ratio of all the individual layers. The electric field intensity in dB$\mu$V/m for an isotropic antenna transmitting the radiation in all directions is given by [16]:

$$E_{dB} = P_{tx}(r)_{dBW} - 20 \log_{10} d - 45.2,$$

where
- $E_{dB}$ [dB$\mu$V/m] is the electrical field intensity which can be calculated using the formula: $E_{dB} = 20 \log_{10}(|E|/1\mu V)$;
- $P_{tx}(r)_{dBW}$ [dBW] from (3) is the transmitted power converted to dBW calculated using the relation $P_{tx}(r) = 10 \log_{10}(P_{tx}(r)/1W)$;
- $d$ [mm] is the distance between the head and the mobile phone.

V. PERFORMANCE ANALYSIS

This section presents performance analysis of HetNets in order to quantify the reduction in transmit power of mobile users due to the uplink power adaptation and SAR improvements. Later, we also discuss the spectral and energy gains of the system under consideration. The presented simulation results throughout this section are based on the parameters which are summarized in Table II.

A. Uplink Power Adaptation

Fig.1 shows the summary of uplink power adaptation over the range of desired target SINR for HetNets and other competitive networks namely macro-only with and without power control and small-cell only networks. The mobile users in a traditional macro-only network without power control transmit with the maximum power over the link, while the mobile users in macro-only networks with power control transmit with the minimum power to meet the desired SINR. Similarly, the mobile users in the small-cell only network adapt their link intelligently and transmit with the minimum power required to meet the quality of the link. The adaptation of transmit
power for HetNets is an average over the minimum transmit power of the mobile users in both the macrocell and small-cell networks. It can be seen clearly that the transmit power of the uplink increases with the increase in desired target SINR. The reduction in transmit power due to fast power control is significant for the networks with power control in comparison with the macro-only network without power control. However, the power adaptation in HetNets is significant due to the small-cell deployment. As an example, for the macro-only network with power control the transmit power corresponding to the cell deployment. As an example, for the macro-only network without power control. However, the power adaptation in HetNets is significant due to the small-cell deployment. As an example, for the macro-only network with power control the transmit power corresponding to the desired SINR, $P_0 = 0.5 \mu W$ is reduced to 835 mW from $P_{\text{max}} = 1 W$. Similarly, for HetNets, the reduction in average transmit power reached approximatively 435 mW.

**B. SAR Reduction**

Fig. 2 depicts the SAR calculated using (7) over the two network configurations. Fig. 2(a) shows the distribution of SAR for a macro-only network with power control over the range of the transmitted power of the mobile user in the network and the distances between the head and the mobile device. The transmitted power of the mobile users adapt according to power control given in (3) over the range of desired SINR as shown in Fig 1. It turns out that the absorption of electromagnetic signals is significant when the distance between the head and mobile phone is in the range (10-20)mm even when the transmitted power is somewhat low due to the lower desired SINR. However, the SAR of the hand held devices increases with the increase in transmit power. This is due to the fact that there are edge mobile users located far away from the reference BS and that are required to transmit with the maximum power under the macro-only network configuration. Similarly, the SAR improvement in HetNets can be seen clearly from Fig. 2(b). The transmitted power of the mobile users is reduced significantly due to the reduction in propagation distance between the mobile user and the respective BS. As an example, for macro-only network with power control the SAR corresponding to the transmit power and distance between the mobile device and head ($P_{tx}, d$) = (835 mW, 10 mm) is approximatively 0.8 W/kg. Similarly, for HetNets, the transmit power of the mobile users decreases significantly and thereby the improvement in SAR is significant. For the pair ($P_{tx}, d$) = (435 mW, 10 mm), the SAR reduction reached...
mobile users are not transmitting with the maximum power anymore. This makes the mobile users to considerably decrease their transmit power and thus reduce the SAR significantly. Therefore, SAR reduction is a special perk offered by the future Heterogenous 5G networks. A number of simulation results are provided to exemplify the reduction in SAR due to the uplink power adaptation. It has been shown that approximately 40% reduction in SAR can be achieved in comparison with the macro-only network through the proposed network level design.

REFERENCES


