FACULTY OF ENGINEERING
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Evaluating the human exposure of a UAV-aided network

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todo

Contents

Acronyms

EIRP Equivalent Isotropical Radiation Power. 13

ICNIRP International Commission on Non-Ionizing Radiation Protection. 7

IEC International Electrotechnical Commission. 14

SAR Specific Absorption Rate. 11, 14, 15, 20

UABS Unmanned Arial Base Station. 7, 9, 10

UE User Equipment. 7, 11, 13–15, 20

1 Introduction

1.1 Outline of the issue

Society is constantly getting more and more dependent on electronic communication. On any given moment in any given location, an electronic device can request to connect to a bigger wireless medium. Devices need more then ever to be connected starting from small IOT sensors up to self-driving cars.

Once again it becomes clear why we're on the eve of a new generation of cellular communication named 5G. This new technology is capable of handling millions of connections every square meter while satisfying only a few microseconds of a delay and providing connections up to 10Gbps [1].

Also in exceptional and possibly life-threatening situations, we rely on the cellular network. For example during the terrorist attacks in Zaventem, a Belgian city. Mobile network operators saw all telecommunications drastically increasing causing moments of contention. Some operators decided to temporarily exceed the limited exposure in order to handle all connections. [2]

Electromagnetic exposure can however not be neglected. Research shows how exesive electromagnetic radiation can cause diverse biological side effects [3]. Because of public concern, the World Health Organization had launched a large, multidisciplinary research effort which eventually concluded that there was no sufficient evidence that confirmed that exposure to low level electromagnetic fields harmfull is [4].

To make sure that the public is not exposed to high level electromagnetic radiation, limits are defined but these restrictions can differ from location to location. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) suggests a limitation of 61 V/m. In Brussels, for example, is a far more restrictive limitation enforced of 6 V/m for all sources [5, 6].

1.2 Objective

In this master dissertation the electromagnetic exposure of a user is investigated taking all prominent sources into account which include the user's own mobile device, basestations and other users their User Equipment (UE).

In order to determine the magnitude of exposure to which users in a certain area are exposed, various values need to be known. Not only the used technology but also the position of users and basestations need to be known. To make this research possible, an existing planning tool is used which gives insight in users and basestation distributions. Bitrates of idividual users, power useage of the different electronical devices and which basestations handels which users. The tool describes in other words a fully configured network. In this way, all needed parameters will be known.

The electromagnetic exposure will then be analysed by applieing the tool in different scenarios. During the simulations it is investigated how various input variables influence the network.

The calculation of electromagnic exposure originating from base stations is discussed in variously discussed in litterture. Papers who convert electromagnetic exposure into a single value is rather limited. Not only how electromagnetic exposure behaves but also related values like power consumption or even coverage.

research question 1: How can a Unmanned Arial Base Station (UABS) network be optimized to minimize global exposure and overal power consumption? What are the effects on the network?

research question 2: What are the advantages and disadvantages of a model as described in research question 1 compared the the already existing pahtloss oriented model.

research question 3: How does the UABS fly height influence uplink and downlink exposure?

1.3 Structure

TODO: update this section

The following chapter 2 exists of several succesive sections explaining how the electromagnetic exposure of a single human being is calculated. The first section 3.2.2 explains how the exposure is calculated between a user and a single femtocell. Section 3.2.2 defines how to combine all exposures from the different femtocells towards a single users. Finaly, section **??** explains how directional antenna's are taken into account.

2

State of the art

2.1 Deployment tool for an UAV network

The tool is also able to calculate a more precisly pathloss since

The calculation of electromagnetic radiation require several input values which need to be known. To fullfill this, a deployment tool developped by The WAVES research group at UGent has therefore developed a deployment tool which distributes UAVs equiped with femtocell base stations. These kind of UAVs will be called a UABS.

A deployment tool for an UAV-aided emergency network is described in [7]. The idea is that in case of a disaster, the existing network might be damaged and won't be able to handle all users who are trying to reconnect to the backbone network. A fast deployable network is suggested in [7] by using UABSs. These are UAVs equiped with femtocell base stations and will be distributed over the disaster area, orchestrated by the deployment tool.

The deployment tool will try to calculate the optimal placement for each UABS and requires therefore a description of the area where the UAV-aided network needs to be deployed. This is done with the use of so-called shape files. Theses files contains tree dimensional descriptions of the buildings present in the area and are key values in approaching results as realistic as possible. Furthermore, the tool also requires a time period and a configuration file containing technical specifications of the type of UABS that is being used. The tool will thereafter randomly distribute users over the area and assigns a certain bitrate to them.

In a second phase, the optimal possition for each UABS is calculated. This is done by trying to locate a UABS above each active user. Two options are possible. If a flighheigt is defined, a basestations is placed above each user at the given height, unless a building is abstructing it's location. Then, no basestation will be located above that user. If no flighheigt is given to the tool, the basestation is located 4 meters above the outdoor user or 4 meters above the building where the indoor user resides. The later is only allowed if the suggested heigt remains below the given maximum allowed height.

Finally, all UABS are sorted on wether they were active or not, followed by the increasing pathloss from each UABS to that user. So the algirtm starts by checking for each active UABS if it can cover the user. If this is the case, the user will be connected to this UABS. If not, the second active basestation with a (slightly) worse pathloss is considered. If no active basestation is suitable, inactive UABS are considered. The user remains uncovered if no UABS is found. The reasoning behind first only considering basestations that are already active is the hight cost that comes allong with each drone.

Up till now, the tool has only calculated some suggestions. The effective provisioning is done in the fourth phase where drones are sorted by the ammount of users it covers. As long as UABS are available in the facility where they reside, UABS are provisioned and its users are marked as covered.

2.2 Electromagnetic exposure

2.2.1 general

The goals of this master disertation is the investigation of electromagnetic exposure.

2.2.2 Uplink exposure

Specific absorption rate

todo: de 10g slaat al op localized, vandaar dat het maar 10g is, anders is het whole-body todo: we kunnen niet sar10gmax gebruiken want This means that the SAR calculations will be worst-case and possibly an overestimation of the real localised SAR. (herwoorden voor plagiaat) Human exposure caused by downlink traffic is a not negligible asset. However, telecommunications is not a one-way street. When connecting to a UMTS network, also uplink data caused by the UE should be considered. UE generates, just like femtocells, electromagnetic waves to which a user is exposed. A part of this radiation goes to the femtocell, another part enters the body of its user. How much electormagnic strenghts enters the body is defined as Specific Absorption Rate (SAR) and is measured with 10g biological tissue which represents the human skin. This value will from now on be expressed as SAR_{10g}. A mobile device induces two types of exposure: local and whole-body.

2.2.3 Downlink exposure

2.2.4 Joining uplink and downlink exposure

2.2.5 Regulations

2.3 Technologies

3

Methodology

3.1 Tool

The goals

3.2 Electromagnetic exposure

3.2.1 Calculation of total whole body SAR10g

The overall SAR_{10g}^{head} can be calculated by a simple sum of individual SAR values [8]. The position of the phone is however unknown. This is because the tool assigns a bitrate to a user depending on the service he is using meaning that users in the network are not only calling but are able of browsing the web aswell. Since calculating the SAR_{10g}^{head} would imply the phone is being hold next to the head, this would result in incorrect conclusions. The induced electromagnetic radiation will therefore be expressed in function of the entire body.

$$SAR_{10g}^{wb,total} = SAR_{10g}^{wb,ul} + SAR_{10g}^{wb,dl} + SAR_{10g}^{wb,neighbours}$$

The first parameter, $SAR_{10g}^{wb,ul}$, will indicate the absorbed electromagnetic radiation in the whole body originating from the users own phone whereas the second parameter $SAR_{10g}^{wb,dl}$ will represent the absorbed electromagnetic radiation by all the basestations in the considered area. As last, $SAR_{10g}^{wb,neighbours}$ specifies the same as the previous but with electromagnetic radiation originating from other users their UE.

3.2.2 Calculating downlink expsure

Calculating exposure towards a single femtocell

To determine the total exposure of a single human being or even of the entire network, the electric-field $\vec{E}$ of a single femtocell i should be calculated. The formula to determine this electromagnetic value E (expressed in V/m) for a specific location is given in equation 3.1.

$$E_i = 10^{\frac{EIRP-43.15+20*\log(f)-PL}{20}} \tag{3.1}$$

TODO: write EIRP - Attenuation (A t)
This formula requires several values to be known. The frequency f on which the tranmitting antenna is operating is expressed in MHz. The other values are explained in 3.2.2 and 3.2.2.

Equivalent Isotropical Radiation Power A directional antenna can achieve gain by focussing it's input power into certain directions. By doing this, some areas experience a decreased radiation power in order to gain radiation power in the other privileged areas. If a theorical isotropic radiator todo: uileggen wat isotropic radiator isexisted, the Equivalent Isotropical Radiation Power (EIRP) is the power it would require to achieve the same power level as the actual antenna's main lob. The main lob is the area of the directional antenna experiencing the most gain. This EIRP value can be calulated as described in eq 3.2.

$$EIRP = P_t + G_t - L_t \tag{3.2}$$

Pathloss At last, formula 3.2 requires the path loss (dB). In order calculate the path loss, an appropiate propagation model is required. Several propagation models exists and the tool already uses the Walfish-Ikegami model [7]. This is because the Walfish-Ikegami model performs well for femtocell networks in urban areas. The chosen propagation model consists of two formulas depending on whether a free line of sight between the user and the basestation exist or not. Both formulas expect a distance in kilometer.

input power hangt af van bs tot bs.

Attenuation todo

Combining exposure

Since the user location in the UAV-aided network is known, the exposure is not calculated for gridpoints but for active users. compared to gridpoints in ref state of art manets -> exosure combineren

$$E_{tot} = \sqrt{\sum_{i=1}^{n} E_i^2} \tag{3.3}$$

Converting downlink electromagnetic exposure to SAR_{10g}^{wb}

Only values for wifi are known but the frequency of LTE is very similar. [9]

3.2.3 Uplink exposure

specific absorption rate into the head

todo: de 10g slaat al op localized, vandaar dat het maar 10g is, anders is het whole-body todo: we kunnen niet sar10gmax gebruiken want This means that the SAR calculations will be worst-case and possibly an overestimation of the real localised SAR. (herwoorden voor plagiaat)

Human exposure caused by downlink traffic is a not negligible asset. However, telecommunications is not a one-way street. When connecting to a UMTS network, also uplink data caused by the UE should be considered.

UE generates, just like femtocells, electromagnetic waves to which a user is exposed. A part of this radiation goes to the femtocell, another part enters the body of its user. How much electormagnic strenghts enters the body is defined as SAR and is measured with 10g biological tissue which represents the human skin. This value will from now on be expressed as SAR_{10g}.

A mobile device induces two types of exposure: local and whole-body. Whole-body exposure can be neglected compared to the much higher local exposure[10]. From now on, SAR_{10g} implicitly means local exposure.

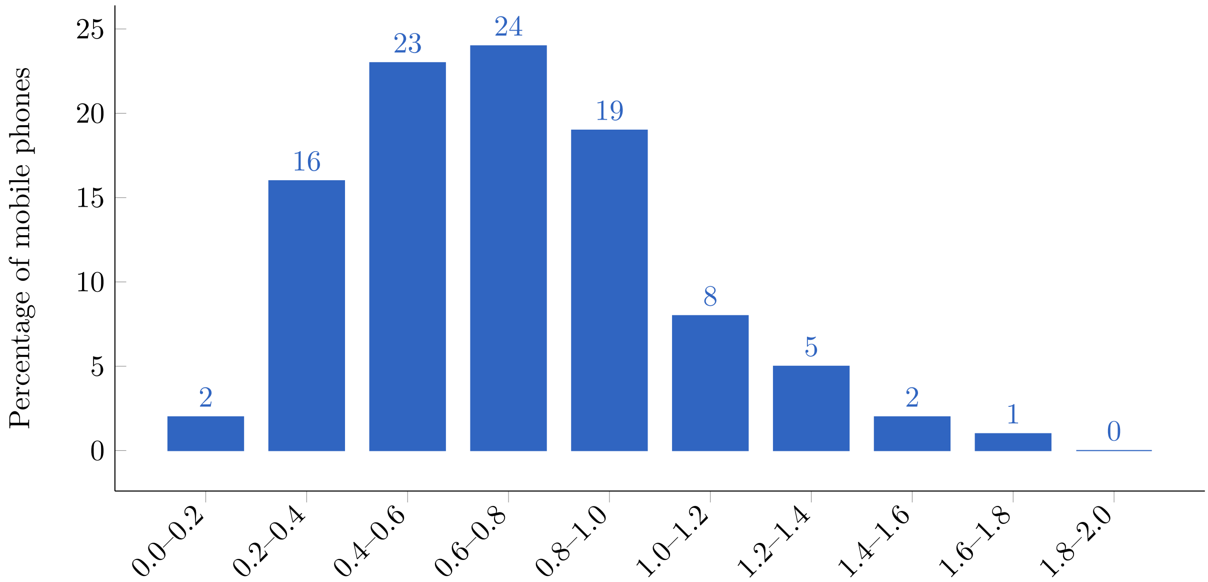
International Electrotechnical Commission (IEC) defines in IEC:62209-2 a maximum for a 10g tissue SAR_{10g}^{max} as 2 W/kg and a maximum for a 1g tissue SAR_{1g}^{max} as 1.6 W/kg. Most countries, including Belgium, enforce the 10g model and will, therefore, be the point of reference for this master dissertation.

The SAR_{10g} values are phone dependent. The reported values by companies of mobile devices are worst-case scenarios meaning that the values are measured when the phone is transmitting at maximum power. This is an understandable decision but won't result in a realistic scenario since modern cellular networks use power control mechanisms to prevent over radiation of a nearby device. UE will therefore never use more energy than necessary to maintain a connection.

To compensate for this overestimation, the actual SAR_{10g} of each user will be predicted. These will, however, remain an estimation since the position of the phone related too the head differs from user to user. For example, by holding the phone differently, a hand can absorb more or less electromagnetic radiation. TODO: bron.

$$SAR_{10g} = \frac{P_{tx}}{P_{tx}^{max}} * SAR_{10g}^{max} \tag{3.4}$$

Equation 3.4 is used to predict the actual SAR_{10g} of a certain user. The SAR value is different for each mobile device. An average is calculated based on 3516 different phones from various brands using an up-to-date German database [11]. When the phone is positioned at the ear, an average of 0.7 W/kg is found with a standard deviation of 0.25 W/kg which are very similar results as in Ref. [10]. The median of 0.67 is used.



todo: xlabel, zeggen dat bovengrens niet inbegrepen is en titel geven.

The P_{Tx}^{max} is for LTE and UMTS 23 Dbm [12, 13].

To predict the effective transmitted power by the UE, the folowing equation is used:

$$P_{Tx} = P_{sens} + PL \tag{3.5}$$

Specific absorption rate for the whole body

```
d = dielectric("Name",'glass',"Thickness",0.00287,"EpsilonR",4.4)
p = patchMicrostripInsetfed("Width",0.0351,"Length",0.02655,
    "GroundPlaneLength",0.06,"GroundPlaneWidth",0.06,"Substrate", d)

pattern(p,2.6e9, 90, "CoordinateSystem", 'polar', "Normalize",true)
pattern(p,2.6e9, 0, "CoordinateSystem", 'polar', "Normalize",true)
```

4

Implementation

4.1 Implementation of downlink exposure

Schrijf over hoe die exposure nu toegevoegd is aan de tool. -Wat deed de tool al? Users en femtocell's uniform verdelen op publiek transport, uabs etc - dat de exposure pas op het einde wordt berekend nadat het netwerk gemodeleerd is.

Algorithm 1 describes the implementation on how to calculate the exposure of a user towards a single base station as described in formula 3.1. Several values need to be known for this to work. In the first place, the path loss is calculated. However, the different path loss values are already calculated during the network initialization phase and can, therefore, be reused on the condition they were saved. By only calculating the path loss once, the time complexity of the tool decreases drastically. Afther this, the gain is calculated by adding the antenna gain to the current input power of the antenna and by substracting the feeder loss as already stated in equation 3.2. In the last place, equation 3.1 is used and the exposure is returned.

To combine all exposures for a specific user, equation 3.3 is translated into algortim 2. Finaly, this needs to be repeaded for every users. Algorithm 3 is used to iterate over each user and each simulation and saves the computed value into the appropriate attribute.

To provide a summary of how the network is performing on electromagnetic exposure, a weighted

Algorithm 1 getExposure

Input user, basestation

Output exposure of a user towards a single basestation

$PL \leftarrow$ path loss between user and basestation

$gain \leftarrow$ getBSantennagain + basestation.getInputPower - getBSFeederLoss

$exposure \leftarrow 10^{\frac{EIRP-43.15+20*\log(f)-PL}{20}}$

return $exposure$

Algorithm 2 getTotalExposure

Input user, basestations[]

Output combined exposures from each basestation for a given user

$E_{tot} \leftarrow 0.0$

for all basestation in basestations **do**

  $E \leftarrow$ getExposure(user, basestation)

  $E_{tot} \leftarrow E_{tot} + E^2$

$E_{tot} \leftarrow sqrt(E_{tot})$

return E_{tot}

Algorithm 3 Calculate and save the total exposure for each user in each simulation

Input users[][], basestations[][]

Output /

for $simulation = 1, 2, \dots basestations$ **do**

  for all user in users[simulation] **do**

    $user.exposure \leftarrow getTotalExposure(user, basestations[simulation])$

average is calculated. This is implemented in algorithm 4 which takes all users for a specified simulation and two weighting factors w_1 and w_2. They respectively correspond to the 50th percentile and 95th of the ordered users' exposure. The two weights get equal importance of 0.5. This is because also higher values should be taken into account and not compensated with very low values. The formula will only use electric field strengths where users are active as opposed to [5] where the area is divided into grids and the exposure is calculated for every gridpoint. The reasoning behind this is that the goal of this master dissertation is to calculate the average exposure of the user and not of the entire area.

The formula first calculates the index where the mean value and the 95th percentile should be located. Afterwards, the exposure is calculated using interpolation if necessary.

Algorithm 4 globalUserExpsoure

Input users[], w_1, w_2

Output Weighted average of the median and the $95th$ percentile electric field strenght

Sort users by E_{tot}

▷ E50

$meanIndex \leftarrow \frac{users.length}{2}$

if users.length % 2 == 0 **then**

$\quad E_{50} \leftarrow users[meanIndex].exposure$

else

$\quad E_{50} \leftarrow \frac{(users[\lceil meanIndex \rceil].exposure)+(users[\lfloor meanIndex \rfloor].exposure)}{2}$

▷ E95 with interpolation

$X \leftarrow users.length * 0.95$

$X_1 \leftarrow \lfloor x \rfloor$

$X_2 \leftarrow \lceil x \rceil$

$Y_1 \leftarrow users[X_1].exposure$

$Y_2 \leftarrow users[X_2].exposure$

$E_{95} \leftarrow Y_1 + \left(\frac{(X-X_1)}{(X_2-X_1)} * (Y_2 - Y_1)\right)$

return $\frac{(w_1 * E_{50})+(w_2 * E_{95})}{w_1+w_2}$

4.2 Implementation of uplink exposure

Analogously to the 4.1, the uplink calculator will determine the uplink exposure and save in the appropriate user object. The calculator starts with iterating over each user in each simulation and calls the getSar() function.

?? is implemented in **??**. The function requires a user as input for which the uplink exposure should be calculated and two constant values which should be declared once. The maximal allowed SAR_{10g} as discussed in **??** and maximal permitted transmission power of 23 dbm.

Also, the actual transmitting power of the UE needs to be calculated using the getActualTransmitPower function.

Both Tx_{watt} and TX^{max}_{watt} are converted to watt. This is because the decibel variant can range from -57 dBm to 23 dBm [**?**]. Converting to Watt results in a solely positive fraction.

After having multiplied with the maximum allowable SAR, the actual uplink exposure is returned.

Algorithm 5 getSar

Input user

Output SAR_{10g}

1: const $SAR^{max} \leftarrow 0.67$
2: const $TX^{max}_{watt} \leftarrow dBm2W(23)$

3: $Tx_{watt} \leftarrow dBm2W(getActualTransmitPower(user))$
4: $SAR_{10g} \leftarrow \frac{Tx_{watt}}{TX^{max}_{watt}} * SAR^{max}$
5: **return** SAR_{10g}

The implementation for getActualTransmitPower is described in **??**. This function requires a user as a parameter and will calculate the real used power for transmission in dBm. Once again, a global constant value is defined describing the maximum allowable transmitting power Tx^{max}_{dBm} expressed in dBm. The predicted transmitting power is achieved by subtracting the path loss between the user and the affective femtocell with the receiver sensitivity of the femtocell. However, this value can't be higher then Tx^{max}_{dBm} , if this is the case the maximum allowable transmitting power is returned instead.

Algorithm 6 getActualTransmitPower

Input user

Output The actual used power for transmition in dBm.

1: const $Tx^{max}_{dBm} \leftarrow 23$

2: $Tx_{dBm} \leftarrow user.getPathLoss() - technology.getFemtocellReceiverSensitivity(user.getRxSNR)$
3: **return** $min(Tx_{dBm}, Tx^{max}_{dBm})$

Algorithm 7 getAttenuation

Input azimuthOffset, elevationOffset

Output attenuation in dBm

const $SAR^{max} \leftarrow 0.67$
const $TX_{watt}^{max} \leftarrow dBm2W(23)$

$Tx_{watt} \leftarrow dBm2W(getActualTransmitPower(user))$
$SAR_{10g} \leftarrow \frac{Tx_{watt}}{TX_{watt}^{max}} * SAR^{max}$
return SAR_{10g}

5
Scenarios

6
Conclusions

todo

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