FACULTY OF ENGINEERING AND ARCHITECTURE

Evaluating the human exposure of a UAV-aided network

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Dankwoord

todo

Contents

Acronyms

DL downlink. 7, 9

EIRP Equivalent Isotropical Radiation Power. 12

ICNIRP International Commission on Non-Ionizing Radiation Protection. 7

IEC International Electrotechnical Commission. 13

SAR Specific Absorption Rate. 13, 21

UABS Unmanned Arial Base Station. 7–9, 15, 22

UE User Equipment. 7, 10, 13, 14, 21

UL uplink. 7

WHIPP WiCa Heuristic Indoor Propagation Prediction. 10

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

It is assumed that in case of a dissaster there is eighter a partial outage of the existing terrestrial infrastructure or the exising network can't cope all requests. The WAVES research group at UGent has therefore developed a deployment tool which distributes UAVs equiped with femtocell base stations to reconnect active users. These kind of UAVs will be called a Unmanned Arial Base Station (UABS). How this tool works is further explained in 2.1.

The electromagnetic exposure of the different active users is currently unknown. The tool will therefore be extended so is capable of calculating exposure. Two types of exposure exists: downlink (DL) exposure and uplink (UL) exposure which is relativly caused by UABS and User Equipment (UE). These values should give insight in how to optimize the network accordingly.

research question 1: How can a 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 3.1.1 explains how the exposure is calculated between a user and a single femtocell. Section 3.1.2 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-aided emergency network

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 Capacity based deployment tool

The described network in 2.1 tries to connect the user to the best basestation based on pathloss while provisioning as least basestations as possible. However, when developing a network it is also important to take electromagnetic field exposure and power consumption into account. Several models have been published on how to calculate downlink electromagnetic field strengts. The calculations in this paper are based on [5] which not only describes DL exposure but also defines a fitness function describing on how the network is performing. Grid points are distributed over the area seperated with a fixed distance. Firstly, the DL exposure in a grid point fom each basestation is calculated and each value is combined resulting in the total exposure in that point. This is repeaded for every single gridpoint. Secondly, the electromagnetic exposure for each grid point is calculated and the 50^{th} and 95^{th} percentile are used to find the global network exposure.

Based on the formula described in equation 3.1 of section 3.1.1, it will become clear that exposure increases exponentially compared to the input power of an antenna and optimizing towards powerconsumption should therefor also decrease it's exposure

However, when taking the electromagnetic exposure and powerconsumption of the entire network, both value's become inversely proportional. Take for instance two users with each their own nearby basestation. When optimizing towards exposure, both basestations will radiate just enough to cover the user near them. When optmizing towards power consumption, it will be better to shut down one of the basestations because each basestation requires a minimal ammount of power. The other basestation will rediate slightly more by using slightly more energy but less then keeping the other basestation alive.

This results in a fitness functions with waiting factors indicating the importance of eighter electromagnetic fields or powerconsumption for a joint optimization of both values. It is espected that this approach is also usefull in a UAV-aided network since drones have a limited battery capacity.

2.3 whipp

Users are not only exposed to electric fields originating from femtocells but also by their own devices. The authors of [8] make use of a WiCa Heuristic Indoor Propagation Prediction (WHIPP) tool. A collection of heuristic algorithms used for designing an optimal indoor network by placing femtocells on the ground plan of the considered building. The paper describes how to calculate localised SAR values originating from a UE to an UMTS femtocell. The paper's model is validated using a Nokia N95. The uplink SAR10g depend on the maximum possible SAR10g and transmit power. The maximum SAR10g is device dependent. Since the deployment tool in this paper is designed voor outdoor usage connecting different unknown types of UE a median of possible SAR_{10g}^{max} phones should be calculated. The actual SAR_{1g}^{max} can't be used since femtocell are short range. Therefor UE will seldom achieve it's maximum possible radiation. Just like [8], a real SAR_{10g} should be predicted.

3

Methodology

todo: Downlink traffic is created by modulation of frequencies caused by a base station. However,

3.1 Calculating downlink exposure

3.1.1 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 3.1.1 and 3.1.1.

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.

3.1.2 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

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

3.2 Calculating uplink exposure

3.2.1 Specific absoption 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. Whole-body exposure can be neglected compared to the much higher local exposure[9]. From now on, SAR_{10g} implicitly means local exposure.

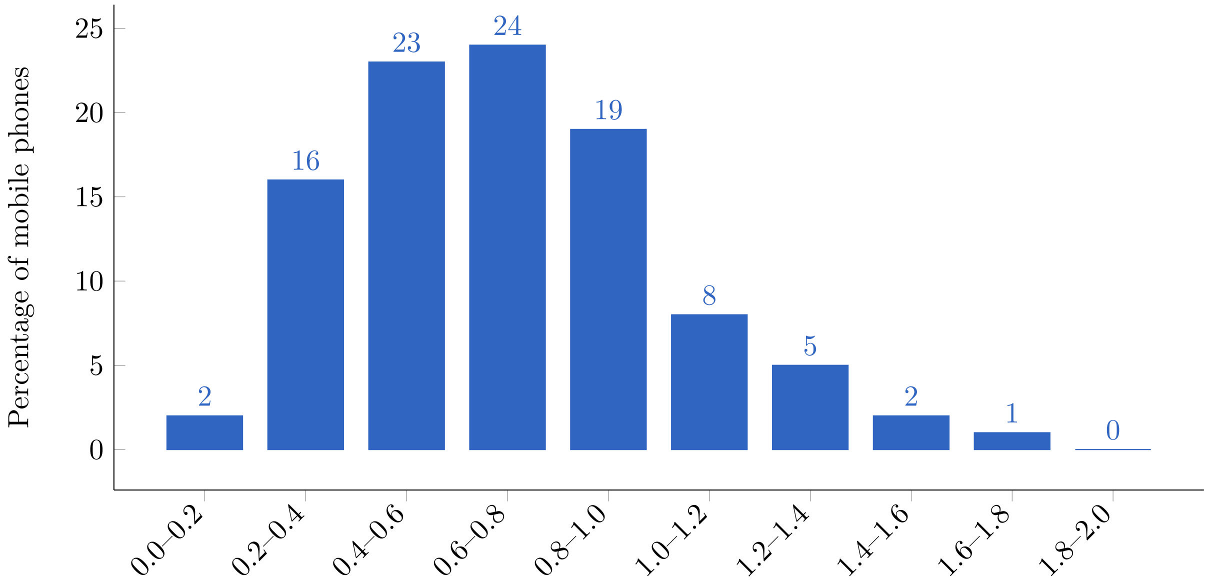
International Electrotechnical Commission (IEC) defines in IEC:62209-2 a maximum for a 10g tissue SAR_{10g}^{max} as 2 W/kg and a maximum for a 1g tissue SAR_{1g}^{max} as 1.6 W/kg. Most countries, including Belgium, enforce the 10g model and will, therefore, be the point of reference for this master 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 [10]. 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. [9]. 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 [11, 8].

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

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

$$P_{sens} = P_{noise} + SNR - G + IL + NF + IF \tag{3.6}$$

3.3 Decision Algorithm

fitnes function: ... - max possible exposure - weighted average (but for each user instead of eatch grid point)

J1 zegt:

The decision for allocating a user to a base sta- tion is changed. In [19], a base station was only

switched on when there was no active base station to which the user could connect. This is no longer the case as discussed in Section 3.2 because this is

not the appropriate decision when optimizing to- wards exposure.

- prevous model between my "generator" class

The tool is extended with a alternative model which will connect users towards exposure and power consumption.

3.4

??Attenuation Formula 3.1 uses EIRP values which assumes an omnidirection antenna which radiation is equal in each direction. These type of isotropic radiatiators are unrealistic since each antenna focusses his energy to certain directions at the cost of decreased radiation at onder sectors. This decreased radiation will be called attenuation and is expressed in dbm.

3.4.1 Defining an antenna

A microstrip patch antenna is choses because it allowes easy production but more important it has a low weight and has a thin profile causing it to be very aerodynamic which is usefull when attaching it to an UABS **??**.

The dimentions of the antenna depend on the frequency it is operating which will be 2.6 Ghz. The formulas from [12] are [13] applied.

$$W = \frac{c}{2 * f * \sqrt{\frac{\epsilon_r + 1}{2}}}$$

Which C the speed of light, f being the center frequency of 2600 Hz and a dielectric contanst of $\epsilon_r = 4.4$ a width of 3.51 mm is achieved.

$$\epsilon_{reff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} * \left(1 + 12 * \frac{h}{W}\right)^{-\frac{1}{2}}$$

The height of the dielectric is choses to be 2.87mm in order to keep the antenna smal and light**??**. ϵ_r is the permitivity constant of the substrate and depends of the used matieral. In this paper, a substrate like glass is chosen because of the high dielectric constant of $\epsilon_r = 4.4$ compared to other matierals like teflon with only a dielectric constant of $\epsilon_r = 2.2$ This is because larger dielectric decreases the dimentions of the antenna patch **??** and therefore indirectly also decreases the dimentions of the entire antenna surface which comes in handy for the limited space on drones. When substituting these values, a ϵ_{reff} of 3.91 is determined.

$$L_{eff} = \frac{c}{2 * f * \sqrt{\epsilon_{reff}}}$$

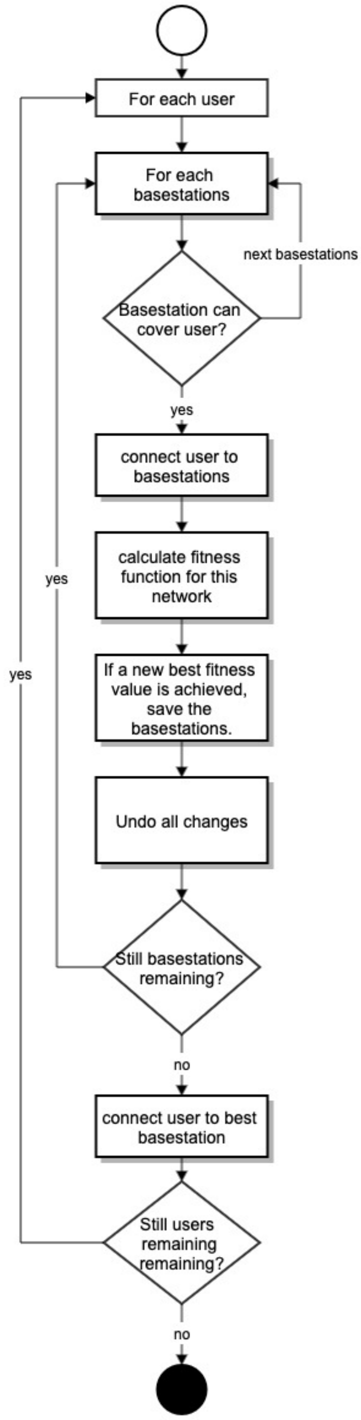


Figure 3.1: Flow chart for the decision algorithm

Applying this formula with the known values of above the L_{eff} results in 29.16 mm.

$$\Delta L = 0.412 * h * \frac{(\epsilon_{reff} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\epsilon_{reff} - 0.258)\left(\frac{W}{h} + 0.8\right)}$$

By substituting the values from above, the length extension determines that ΔL equals 1.3071 mm.

Finally can the lenght of the patch be calculated using the expression: $L = L_{eff} - 2 * \Delta L$ which result in 26.55 mm which result in an antenna like 3.2.

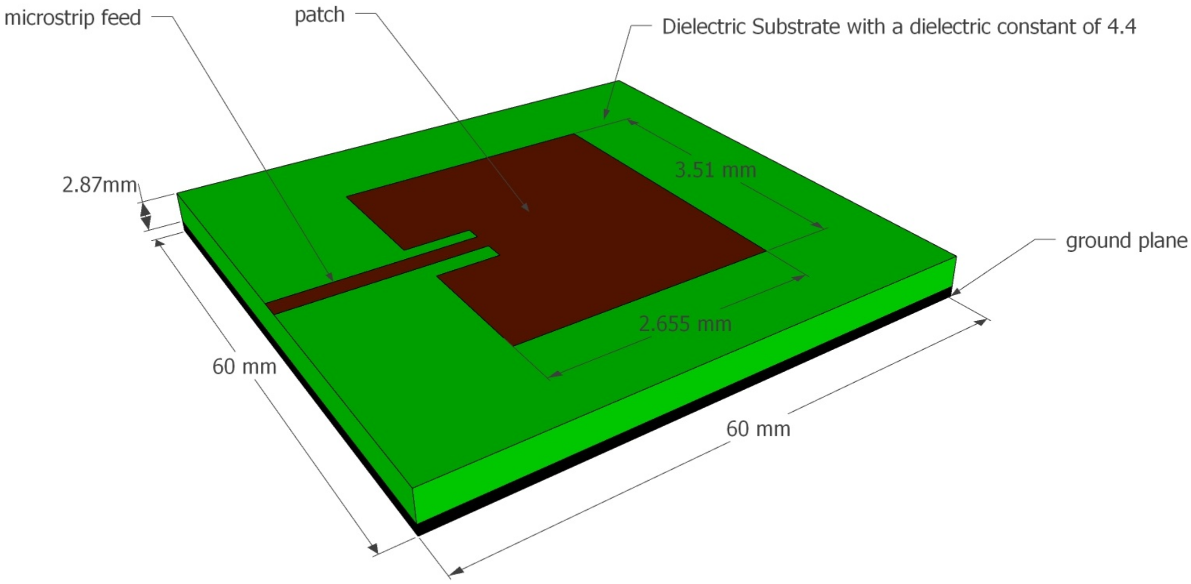


Figure 3.2: Design of the microstrip patch antenna.

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 ← path loss between user and basestation
gain ← getBSantennagain + basestation.getInputPower - getBSFeederLoss
exposure ← 10^((EIRP−43.15+20∗log(f)−PL)/20)
return exposure
```

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

Algorithm 2 getTotalExposure

Input user, basestations[]

Output combined exposures from each basestation for a given user

```
E_tot ← 0.0
for all basestation in basestations do
    E ← getExposure(user, basestation)
    E_tot ← E_tot + E^2
E_tot ← 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, . . . basestations do
    for all user in users[simulation] do
        user.exposure ← 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**

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

else

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

▷ 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 3.2.1 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_{watt}^{max} 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}

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}

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_{dBm}^{max} 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_{dBm}^{max} , 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.

const $Tx_{dBm}^{max} \leftarrow 23$

$Tx_{dBm} \leftarrow user.getPathLoss() - technology.getFemtocellReceiverSensitivity(user.getRxSNR)$

return $min(Tx_{dBm}, Tx_{dBm}^{max})$

5

Scenarios

5.1 Downlink exposure versus power consumption

The authors of [7] proposed a fitness function for a joint optimization of the global network exposure and the overal power consumption. This idea works fine for high powered basestations capable of covering multiple users. For example when optimizing towards exposure, the algorithm will decide to activate multiple low powered basestations. This has a negative influence on the overal power consumption of the network because each basestations requires a minimal ammount of power to be active. Analogously whill the algorithm shut down basestations when optimizing towards power consumption. Active basestations will slighty increase their individual power consumption and therefor also increase electromagnic radiation to be able to cover more users. This power increase is ofcourse less then the activation of a new basestation.

The deploymentool described in this paper makes uses of UAV's, equiped with femtocell base stations. These are low powered devices compared to basestations used in the terrestrial network with a more limited range. Most users are therefor connected to the UABS placed directly above them. By increasing eighter the ammount of users or the maximum input power. The graph below show shows the amount of users compared to the ammount of users that are connected to their own basestations.

It becomes clear that this fitness function will primarly optimize towards exposure (unless with a lot of users)

5.2 Downlink exposure versus drone kost

- Optimizing towards exposure and kost might be a better idea - oorspronklijke code deed dit ook al door eerst drones te overwegen die reeds actief waren - zijn resultaten gelijkend? - ook deze functie wordt gelimiteerd door het maximum bereik van een femtocell

5.3 Pathloss model versus exposure optimized model

The original model used in the tool will first consider basestations that are already active. The reasing behind this is the high costs that comes with the deployment of each drone. Therefor it might be beter to not optimize towards power consumption but rather towards cost.

The fitness function will be changed so that the current cost of the network is a fraction of the total possible cost.

waarom is de exposure is mijn model zoveel lager? ten koste van wat?

5.4 Uplink and downlink exposure versus fly height

- expected that pathloss decreases - radiation will increase because of the heigt but since you loose less, the exposure might not increase that mutch and you may cover more users.

5.5 Uplink and downlink exposure versus horizontal distance

5.6 Amount of users versus exposure

6 Conclusions

todo

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