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Mobility-aware power control in MBSFN

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Abstract Multimedia broadcast/multicast service over a single frequency network (MBSFN) within LTE systems is a feature that allows synchronous broadcasting of common data among neighboring cells. With MBSFN operation, mobile broadcast/multicast users are able to use inter-cell interference in a constructive way and to achieve increased bit-rates compared to when conventional broadcasting is used. In this manuscript, we present our work on the optimization of the power control for future mobile networks that employ MBSFN transmission. We propose a novel simulator and system optimizer that can minimize the individual cell's transmission power by taking into account the changing positions of users. The system optimizer is based on a novel genetic algorithm, which is resistant to entrapment in local optima and makes use of mutations over the previous solutions in order to optimize the power consumption given the new users' positions. The optimizer's engine can be used in conjunction with the simulator or can be easily modified to receive real-time measurements from a real LTE network as an input. In order to read descriptions of the various scenarios, the simulator uses the eXtendable Temporal Network Description Language, a language that is also specified in this manuscript.

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1 Introduction

The network's resource usage when data have to be broadcasted to many recipients is one of the main challenges that many mobile technologies are facing nowadays. The data that need to be broadcasted are usually multimedia data with high quality requirements and therefore high bandwidth demands. In addition, the increasing demand for wireless multimedia applications stresses the need for new transmission technologies that use the fewest possible network resources [10,17].

Being introduced in 3rd Generation Partnership Project (3GPP) Release 6, multimedia broadcast/multicast service (MBMS) constitutes the ideal technology to confront the high requirements for multimedia content delivery. In Long Term Evolution (LTE) networks, MBMS will achieve high transfer rates by employing the MBMS over a single frequency network (MBSFN) transmission. In MBSFN operation the cells transmit synchronized data so that the interference of the cell is no longer destructive. The cells' signals, that form what we call an MBSFN area [3,14], interfere constructively, increasing the signal to noise ratio (SNR). In turn this increases the spectral efficiency (SE), i.e., the throughput achieved with a certain frequency bandwidth, of the data channel and therefore the total available bit rate.

MBSFN can therefore be considered as a special case of point-to-multipoint (PTM) transmissions where the data are transmitted simultaneously over the air from multiple tightly time-synchronized cells. Although PTM transmissions is a fairly resource efficient scheme, it suffers from inter-site destructive interferences, especially at the cell edges, unless guard zones are used [2,12], i.e., each cell transmitting in a frequency that shares with none of its neighbors. Therefore, MBSFN is extremely beneficial at the cell edge, where transmissions are translated into useful signal energy and hence the received signal strength is increased; while, at the same time the interference power is largely reduced.

Since the energy consumption in the access network and the green movement are major challenges in the domain of mobile telecommunications [7], this manuscript proposes a novel simulator and system optimizer that selects the optimal MBSFN area and adjusts the transmission power of the simulated cells in order to minimize the power consumption of the network; while simultaneously keeps the quality of service (QoS) of the users in the required levels. The system optimizer is based on a novel genetic algorithm, which is resistant to entrapment in local optima and makes use of mutations over the previous solutions in order to optimize the power consumption. This algorithm supports real-world coordinates for users and cells, allows arbitrary positioning for base stations, supports moving users and uses an innovative network description language as input. Since the genetic algorithm uses mutations over the previous solutions, the examined solutions do not differ significantly from the previous ones. The simulation experiments show that this fact corresponds to regular user mobility in mobile networks, which normally do not differentiate the user distribution significantly and therefore the next optimal system configuration is not expected to differ significantly from the previous ones. It is implemented in a graphical tool, named DAGraCO [11], which is written in LÖVE [15], a framework for writing 2D applications using Lua [16] programming language.

The simulator takes into account the characteristics of MBSFN in LTE mobile systems. The cells that form the MBSFN area transmit in sync independently of whether they contain users or not, increasing in this way the SE of users in the topology. The synchronized transmission of different cells can constructively interfere to some degree depending on the distance each signal travels before it reaches the user. Another important contribution of this work is the definition of the eXtendable Temporal Network Description Language (XTNDL), a language that can be used for the description of mobile network's topology as well as the user mobility scenarios.

The remainder of the manuscript is structured as follows: past scientific works and technical documents related to the manuscript's topic are briefly presented in Sect. 2. In Sect. 3, we define the XTNDL language and in Sect. 4 we present the proposed optimization algorithm. Sect. 5 describes the experiments demonstrating the operation of the proposed algorithm. Finally, our conclusions and some possible next steps are described in Sects. 6 and 7, respectively.

2 Related work

Radio resources management is an issue extensively considered by the research community also in recent studies [13,19]. Single frequency network for broadcasting is an operation, which can be integrated for the support of efficient broadcasting in any system that utilizes OFDM. Therefore, not only MBMS in mobile LTE networks but also the terrestrial digital TV broadcasting systems, such as DVB-T, are well-suited to this type of operation. For mobile LTE networks, different aspects of MBSFN have been studied so far, not only in previous research works but also in technical papers published mostly by 3GPP.

MBSFN was initially proposed for LTE, in [1], as a mean to improve the performance of MBMS. Additionally, in [2], 3GPP assesses the SE and the resource efficiency (RE) under varying numbers of MBSFN assisting rings, i.e., rings of cells transmitting using MBSFN although no users in them are interested in the multicast data transmitted. The RE is a metric that takes into account the SE of all cells in the examined topology and shows how efficient the system resources are used for the transmissions.

An early scientific work on MBSFN is presented in [18]. In this paper, the authors propose an analytical model to obtain SINR and the achieved SE over a given cell in the network. This analytical approach also considers the shadowing in MBSFN is used for the evaluation of the dynamic MBSFN approach. A 4-step procedure for the calculation of most efficient modulation and coding scheme (MCS) in terms of SE is proposed in [8]. Based on this procedure, the authors evaluate four approaches that can be used for the selection of MCS during MBSFN transmissions over LTE networks. In [6] the same authors define an analytical model for the calculation of the SE performance achieved in an MBSFN area. They also consider a dynamically changing user distribution as well as different selections of MCSs. Based on the SE performance, they determine the MCS that either maximizes or guarantees a target SE for the corresponding user distribution.

A first step of the work leading to the results of the present manuscript is presented by the same authors in [5]. In this paper our research team examined the effect of the combination of PTM and MBSFN with the help of a novel optimization algorithm. Using the simulation results presented in [2] we approximated the SE of individual cells based on the number of assisting cells around them. Furthermore, we produced some promising results regarding the usage of strategically placed MBSFN assisting cells. In [9] we presented a second version of the previous algorithm that also includes support for real-world coordinates for users and cells, thus allowing arbitrary positioning for base stations which can form irregular grids and, subsequently, the simulation of real-world networks and not just simplified hexagonal grids. Another important contribution of [9] is the introduction of a genetic algorithm in the optimization part of the previously proposed mechanism, which is more efficient compared to the implementation presented in [5]. The algorithm was implemented in a graphical tool, namely the AccuGraCovO [4].

To conclude our literature review, we should mention that no MBSFN-optimization tool supporting adaptation to user mobility has been presented so far in the existing scientific and technical publications. To this direction, our work exploits the properties of an innovative genetic algorithm, which makes use of mutations over the previous solutions, in order to optimize the power consumption for the subsequent user distribution. It is important that the solutions examined by the algorithm are based on mutating the previous ones, since the regular user mobility normally differentiates the user distribution in a limited extend and therefore the next optimal system configuration is not expected to differ significantly from the current one. Another important innovation of this work that is the definition of a language, namely the XTNDL, that can be easily used for the description of mobile network's topology as well as the user mobility scenarios. This language can be received by our system as an input and be translated in order to generate the simulation scenario.

3 XTNDL description

One of the major contributions of this work is the definition of the XTNDL, a language invented as a scenario description language for mobile networks. It can be used for the description of mobile network's infrastructure as well as the user mobility scenarios. eXtendable Temporal Network Description Language is easily extendable, since it defines only the structure and leaves the minimum data requirements to the simulator.

In this study, XTNDL is used for the definition of the mechanism's input data, which are basically a list of associative arrays fully describing each simulation scenario. Each array in the list describes precisely the position, movement and all related data for a specific type of entity. User's and cell's base stations are the fundamental entities in our case, therefore, a single array describes users while another array describes cell's base stations. The arrays store data in entityID–entityData pairs. The entityID can be any string, e.g., *user*1, or even a number and will be subsequently used as a reference to a specific entity. In either case the entity array stores another associative array in every index. This associative array is further indexed by timestamps, i.e., seconds represented with floating point numbers. For example, if the input data are contained in a list named *inputdata* then item *inputdata[5][3.55]* contains the position of the user with ID equal to 5 for 3.55 s (t = 3.55 s) after the beginning of the simulation.

Additionally, each entity array contains arrays of data describing the entity's position at that point in time and may contain any number of generic options in the "general" field. This field should store data about the entity that are permanent. The special field "interpolate" may provide a custom function that will be used for interpolating the data between points in time. If this function doesn't exist, linear interpolation should be used by the simulator for every named piece of numerical data that appears in one or more points in time. For non numerical data the default is to interpolate by using the value of the oldest of the two values. For example, if the option named "low battery" is false (false is a non-numerical value) at t = 4 s and true at t = 4.1 s then it should be assumed that "low battery" is false in [4, 4.1].

Based on the above description, a possible scenario is the one described by the following list of associative arrays:

$$inputdata = \{ \{[7] = \{x = 2, y = 2\}, [8] = \{x = 15, y = 15\}, [inf] = \{x = 15, y = 15\}, \}, \{[2] = \{x = 0, y = 0\}, [12] = \{x = 24, y = 24\}, \}, \}$$

The above list contains information about two users. The first user appears, i.e., turns on the multicast service, in the network at t = 7 s being at the position (2,2). He starts moving at a constant speed towards (15,15) and arrives there after 1 s (t = 8 s). He remains at (15,15) forever. The second user appears at t = 2 s and position (0,0). He moves towards (24,24) where he arrives at t = 19 s and disappears.

eXtendable Temporal Network Description Language also provides functions to populate this list of associative arrays easily. The user may write the list manually or use the XTNDL functions to populate the list more easily. A single object called $world$ is used providing object oriented functions to add users and cells as well as move users around.

The following functions are provided by the $world$ object:

- $world : create\_cell(x, y)$: Creates a single cell at position (x, y).
- $world : create\_user(x, y, t)$: Creates a single user at position (x, y) and time t. Returns a $user$ object.
- $world : create\_user\_group(x, y, total, radius, t)$: Creates a group of total users around position (x, y) at a maximum distance of $radius$ and time t and returns the $user\_group$ object.

The $user$ object provides the following functions:

- $user : move\_to(x, y, t)$: Moves the user to (x, y) in t seconds.
- $user : stay(t)$: The user waits at the same position for t seconds.
- $user : set\_speed(s, d, t)$: The user moves at s m/s towards the direction of the angle d for t seconds.

The *user_group* object provides the same functions as the *user* object and additionally the following function: $user\_group : change\_radius(r, t)$ which changes the radius of the group to r in t seconds.

For example, one could use the following functions to create the first user:

$user = world : create\_user(2, 2, 7)$
$user : move\_to(15, 15, 1)$
$user : stay(inf)$

The second user is created as follows:

$user2 = world : create\_user(0, 0, 2)$
$user2 : move\_to(24, 24, 10)$

If the second user disappears because he exited the simulated area, the last command should be replaced by:

$user2 : set\_speed(math.sqrt(24^2 + 24^2)/10)$

Another scenario involving 20 users, in a circle with a radius of 1m, moving from position (4,4) to (3,7) in 5 s could be written as:

$users = world : create\_user\_group(4, 4, 20, 1, 0)$
$users : move\_to(3, 7, 5)$

In order to populate the world with cells at positions $(9, 3)(3, 9)(9, 9)$ and $(3, 3)$, the following commands should be issued in the script:

$world : new\_cell\{x = 9, y = 3\}$
$world : new\_cell\{x = 3, y = 9\}$
$world : new\_cell\{x = 9, y = 9\}$
$world : new\_cell\{x = 3, y = 3\}$

To manually add a user without using the high level functions, the following list should be created manually:

$table.insert(world.users,$
$entity\{[0] = \{x = 1, y = 1\}, [10] = \{x = 10, y = 10\},$
$[math.huge] = \{x = 9, y = 10\}\})$

4 Network modeling and optimization

In this section we present the network modeling and the analytical processes, which we conducted towards the design and implementation of our simulation tool. We also provide details on the proposed genetic algorithm used for the mobile network's optimization in terms of power consumption.

4.1 Network setup

One of the basic notions in this work is that of the MBSFN area, which is defined as the group of time-synchronized cells that participate in the MBSFN operation. Each cell in this group may or may not contain user equipments (UEs) that have subscribed to receive the MBMS service, i.e., the multicast users. The cells containing multicast users are called interested UE drop location cells, whereas the rest cells that do not contain multicast users are called assisting cells. The assisting cells broadcast the MBSFN data while they do not actually contain any users that have subscribed to receive the MBMS service. Instead, these cells assist the UEs of neighboring cells to constructively combine their transmissions. This is the main difference between MBSFN and PTM transmission; MBSFN transmissions are time-synchronized so their combination can be constructive, while PTM transmissions cause interference to other transmissions in the vicinity.

Our goal is the optimization of the network in terms of power consumption but also, at the same time, to keep the SE above a satisfactory level, i.e., 1 bps/Hz for the 95 % of the multicast users. Therefore, our optimizer is able to estimate the SE for any user utilizing the network based on the positions of the nearby antennae. The input of this lower level calculation is the 2D coordinates of the antennae and the users in double precision floating point arithmetic. In that way, our optimizer can process any arbitrary network topology even those that are not composed of regular hexagons unlike previous works, e.g., [2] and [5], where the examined networks were simplified topologies consisted exclusively by regular hexagonal cells.

For the construction of the network topology, the first step is to assign the user to a cell that will be considered as his primary serving cell. Our simulator selects the link having the highest power level at the position of the user. In this way an area is created around each cell. Any user located in this area uses will use the corresponding cell as his primary cell. The areas become wider as the transmission power of the cell increases since a user will then have to move much further away from his primary cell's base station in order for the signal of a neighboring cell to surpass the power of his primary signal. This operation creates a network topology similar to a weighted Voronoi diagram, such as this depicted in Fig. 1, with the weights being each base station's transmitting power.

At the end of the operation for the primary cell assignment, the network topology includes an association between all the users and their primary cells. This association is depicted in seen in Fig. 2.

After the primary cell assignment, the mechanism proceeds with estimating the SE of the communication over each user's primary link. For the calculation of the SE for each

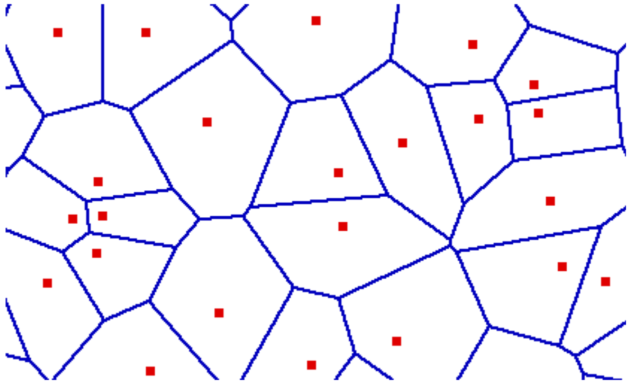


Fig. 1 The simulated network topologies are, essentially, Voronoi diagrams

user, the Shannon theoretical limit multiplied by an attenuation factor is used:

$$SE = 0.6\,log_2\left(1 - \frac{S}{N+I}\right) \tag{1}$$

For each of the adjacent cells, the signal power that the user experiences is calculated. For this calculation, the COST-231 path loss model is used. Additionally, for cells other than the primary one, the timing of the signal arrivals is taken into account, since, according to [18], the exact timing of the secondary signals determine the portion of the signal power that will count as signal (S) or interference (I), in the above formula. Given that the simulated cells can transmit using different cell characteristics, such as base station power level and antenna height, a user's primary cell is not necessarily the one closest to him. As a result, some of the secondary signals can arrive earlier than the primary one. To achieve maximum constructive interference the two signals have to be received in sync. Otherwise the overlapping portion of their cyclic prefixes will determine what portion of the interference is considered constructive as given by the formula in (2) [18] where τ is the time shift between the neighboring signal and that of the primary cell and T_{CP} is the duration of the cyclic prefix.

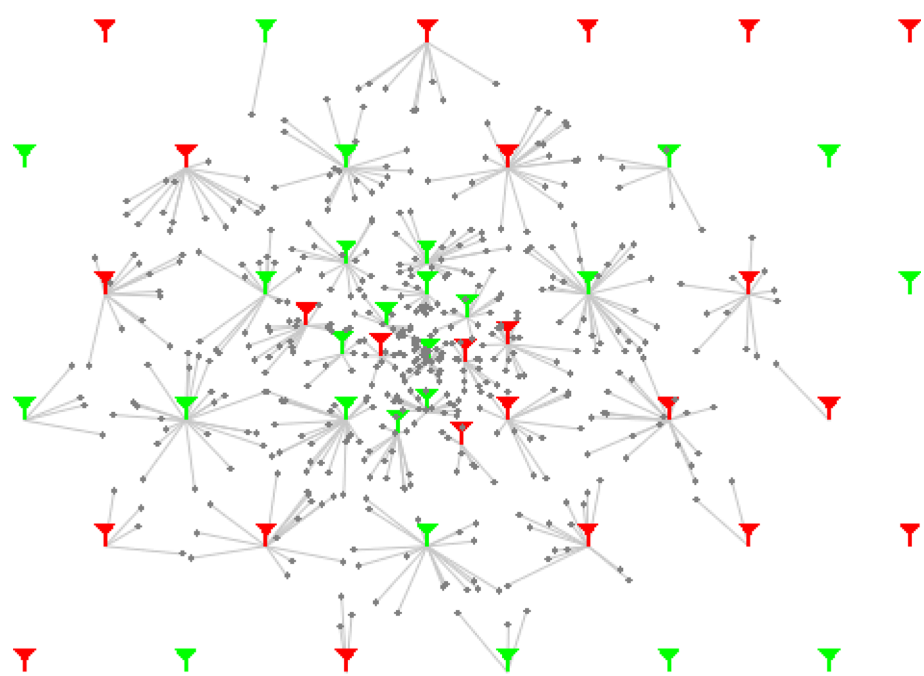
$$w(\tau) = \begin{cases} 0, & \text{if } \tau < -T_u \\ 1 + \frac{\tau}{T_u}, & \text{if } -T_u \leq \tau < 0 \\ 1, & \text{if } 0 \leq \tau < T_{CP} \\ 1 + \frac{\tau - T_{CP}}{T_u}, & \text{if } T_{CP} \leq \tau < T_{CP} + T_u \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

After calculating the SE for every user, it is trivial to check if at least 95 % of the users have $SE > 1$bps/Hz.

4.2 Proposed algorithm

The algorithm emulates the network in real time. It does small, semi-random changes to the transmission power of the cells and after simulating the network it decides whether the changes should be kept or roll-back should be executed. Each user is able to mark the three closest cells to him, in terms of path loss. These marked cells tend to increase their power while unmarked cells tend to decrease it. For example a marked cell transmitting with 10 W can be altered randomly to transmit at a power level between 9.8 and 10.4 W. If it was unmarked it would be randomly changed to some power level between 9.6 and 10.2 W. For all cases, the power levels are defined at a step of 0.1 W.

Fig. 2 A network topology with users connected to their primary cell



If the algorithm was applied to a live network it would constantly need to know the bit-rate that each client achieves and the path loss between each user and cell. In our case the user positions are known so the bit-rate for each user is estimated and is fed it to the optimization part of the algorithm in real time. That means that one second of simulation corresponds to one second of executing the algorithm. It is possible to change that ratio if needed for the purpose is to show how the algorithm could cope with real time updates of the user bit-rates and not to actually optimize the network.

In an real network we would be unable to have instantaneous evaluations of the network. To accommodate this, each simulation and evaluation is broken up into phases.

Algorithm 1 phase1 (cellPowers, oldCellPower, totalCells)

$score \leftarrow evaluate(cellPowers, users_t)$
{Save a snapshot of the current network configuration.}
for $i = 1$ to $totalCells$ **do**
  $oldCellPower_i \leftarrow cellPowers_i$
end for
$mutate(cellPowers)$
$oldScore \leftarrow score$
$phase2(cellPowers, oldCellPower, totalCells)$

Phase 1 The current state of the network is evaluated. A snapshot of the current network configuration (an array containing the transmission power of every cell in our case) as well as the current score of the network is saved in memory for use during the next phase. The network topology is randomly changed in terms of transmission power of each cell. This optimization round ends. The next round will be a phase 2 round.

Phase 2 The current state of the network is evaluated. If it is better then the last known state then the last known network coverage is dumped and the current network coverage is saved in memory for use during the next round. The current round ends and the next round will be a phase 2 round again. If, on the other hand, the last known network coverage had a better score than the current coverage, then the algorithm rolls back to this network coverage and end the round. The next round will be a Phase 1 round.

The overall algorithm is summarized in the flowchart of Fig. 3.

Between rounds a short time interval is needed to redraw the screen. This time in a real live application of the algorithm would be spent evaluating the bit-rates achieved by each user. If this measurement is bigger than the amount that the algorithm spends drawing the screen then it would be trivial to delay the screen redraw to simulate the actual delay of user bit-rate measurements.

Whenever the network topology solution needs to be assessed, the algorithm runs separately for each user. The steps followed by the algorithm are described below:

Algorithm 2 phase2 (cellPowers, oldCellPower, totalCells)

$score \leftarrow evaluate(cellPowers,)$
{Save a snapshot of the current network configuration.}
if $oldScore < score$ **then**
  {The change led to a better score. It is kept.}
  for $i = 1$ to $totalCells$ **do**
    $oldCellPower_i \leftarrow cellPowers_i$
  end for
  $oldScore \leftarrow score$
  $mutate(cellPowers)$
  $phase2(cellPowers, oldCellPower, totalCells)$
else
  {The change did not lead to a better score. Discard it and try a new one.}
  for $i = 1$ to $totalCells$ **do**
    $cellPower_i \leftarrow oldCellPowers_i$
  end for
  $phase1(cellPowers, oldCellPower, totalCells)$
end if

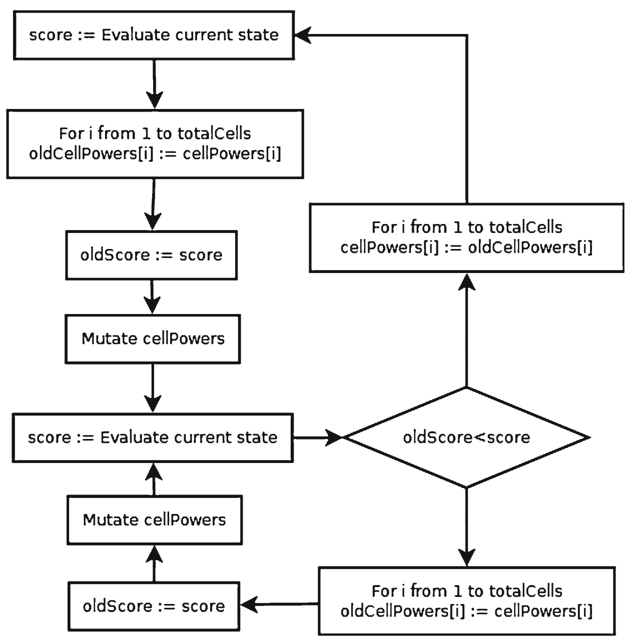


Fig. 3 Flowchart of the overall algorithm

(1) First, the distance of each user from each base station is measured. Based on that distance, the received signal power is estimated using the COST 231 path loss model.
(2) The next step is to estimate the SE of each user based on (2).
(3) It is examined whether the solution is acceptable, i.e., the achieved SE is over a threshold value that would also secure that the achieved bit-rate is over some satisfactory service threshold.

If the optimization algorithm is to be applied over a live network then each user's bit-rate should be measured directly. In our trials we initially used a multipart function where if more than 95 % of the users have a satisfactory bit-rate, the

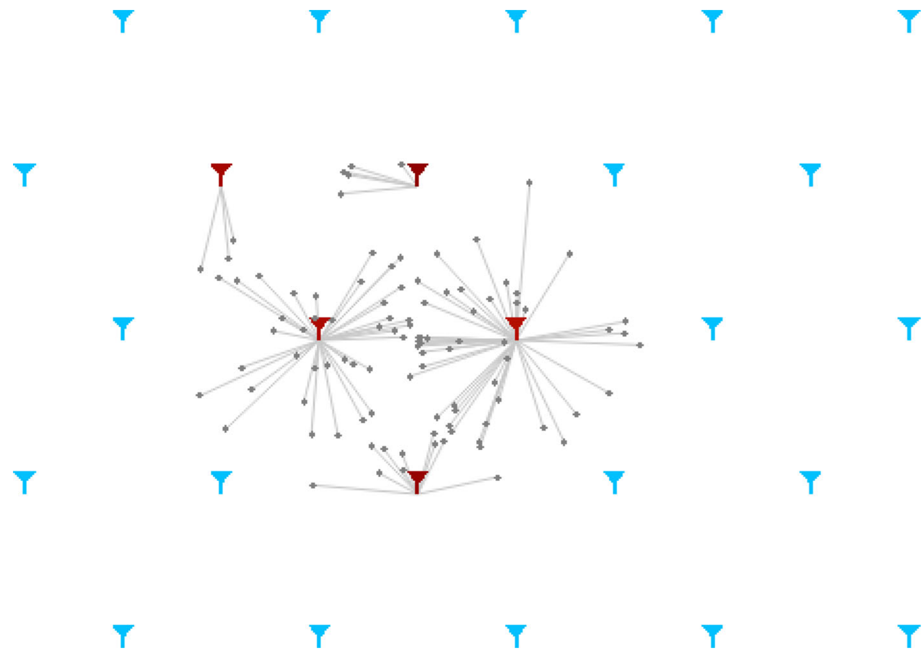


Fig. 4 A grid-like network topology and the proposed coverage

score used for the evaluation of the network's power consumption will be $1+\frac{1}{power}$. This figure is a number in $(1, \infty)$ and the higher score is achieved, the better the system's performance is. If less than 95 % of the users are satisfied then the score is the portion of the users satisfied, which is a number in $[0, 0.95)$, i.e., again the higher score the better. The non-continuity in the score graph in the interval $(0.95, 1]$ does not affect the optimization algorithm since the algorithm just tries to maximize the score. Nevertheless, taking into account that this is a real time algorithm and in order to preserve the algorithm's efficiency even when users are moving, we had to make the transition smooth and continuous. Given that the algorithm keeps the amount of satisfied users barely over 95 %, then the users' mobility can often cause the percentage of satisfied users to fall slightly below 95 %. This in turn would cause the algorithm to immediately increase the network power levels as a compensation for this. The side-effect of this reaction is that the algorithm could, in the meantime, have converged into a specific optimal solution, which would possibly be destroyed. Therefore the transition is needed to be smooth enough so that in case the satisfied users go slightly below 95 %, the algorithm will not destroy the overall solution, and the potential big decrease in the evaluation score will be avoided.

5 Simulation experiments

This section presents the results of our experiments for two distinct scenarios. The first scenario examines realistic and hex grid topologies with static users. For each topology we present the proposed deployment and a graph of the algorithm's progress towards the proposed deployment. Main target of this scenario is to present how the algorithm selects the optimal MBSFN area and how the power consumption and percentage of satisfied users are affected during the optimization process.

The second scenario assumes moving users and therefore the data that processed are not only spatial but also temporal. Our goal is to illustrate that the algorithm makes conservative changes which will not cause serious service disruptions and which will slowly drift towards better network coverage. This scenario also presents the power consumption and percentage of satisfied users during the optimization process in order to examine the performance of the algorithm.

5.1 Static users scenarios

5.1.1 Simulations of grid-like topologies

The first experiment of the static users' scenario is performed over a hex grid-like topology, where the antennae are placed with horizontal and vertical distance between them equal to 1,000 m. Two different user distributions are examined in order to reveal the performance of the proposed algorithm.

According to the first user distribution 100 static users are uniformly placed around an almost central point of the topology and inside a fixed circle with radius equal to 1200 m. As depicted in Fig. 4, the corresponding user distribution leads to higher user concentrations near the center. During the optimization process, the algorithm turns off the cells that are away from the users, since they do not efficiently contribute in the transmission of the MBSFN data, with main target

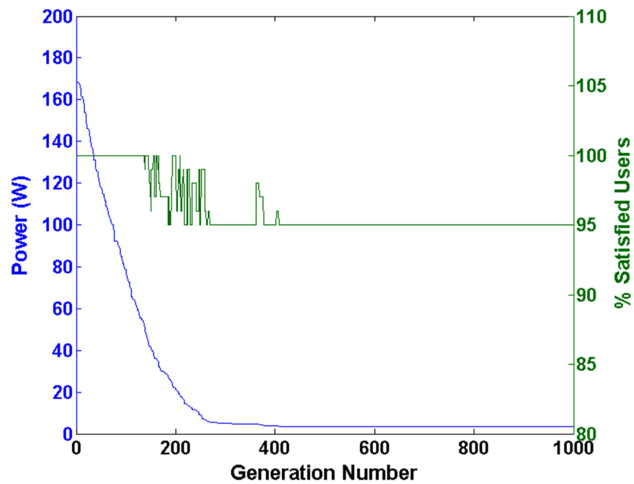


Fig. 5 Power consumption and percentage of satisfied users during the optimization process (100 users in total)

to minimize the overall power consumption. These cells are presented with cyan color in Fig. 4. As a result, the optimal MBSFN area consists of five cells (red colored cells).

Figure 5 illustrates the power consumption and percentage of satisfied users during the optimization process (which required 1000 generations of the genetic algorithm) for the specific user distribution. It is obvious that the algorithm achieves to reduce the power consumption of the network by turning off the cells that do not constructively participate in MBSFN, while simultaneously it adjusts the power of the cells that participate in the MBSFN transmissions in order to keep the percentage of the satisfied users above the 95 % threshold. After the optimization process, both targets are achieved according to Fig. 5. The total power consumption reduces from 170 to 5 W, a total reduction of 97.06 % compared to the random initial configuration, while the percentage of satisfied users always remains above the threshold.

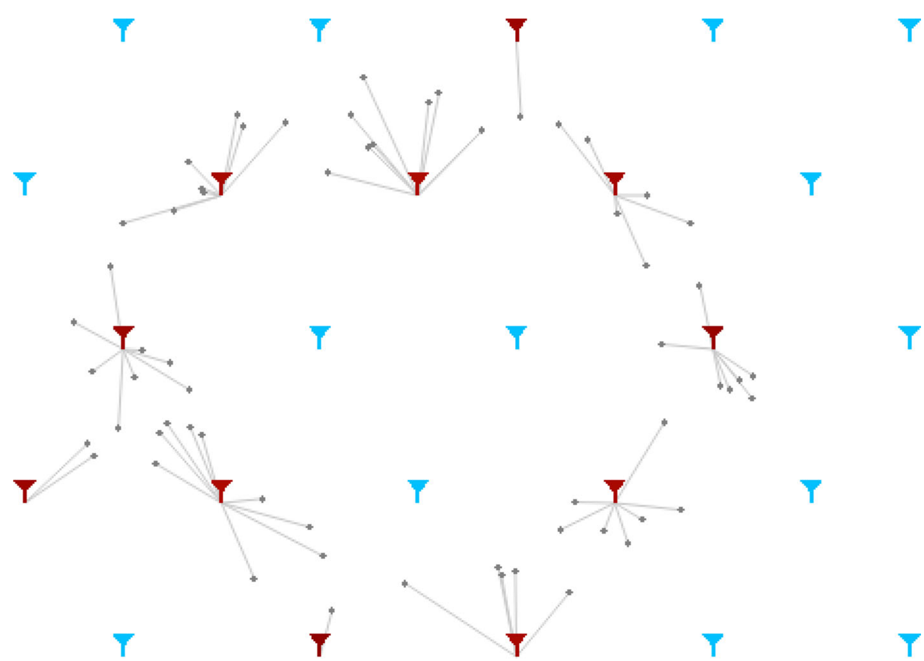
The second user distribution assumes 63 users placed in a ring like formation as illustrated in Fig. 6. This user distribution was selected in order to investigate whether the algorithm would suggest that the central cells should be included in the MBSFN area or not. Contrary to the results of work [5], we notice that the addition of assisting cells is not the optimal strategy as long as these cells do not contain users. To this direction, the three central cells are turned off and do not participate in the MBSFN transmissions. However, the optimal configuration includes some cells that only serve a single user or even a couple of users.

Figure 7 depicts the progress of the algorithm over 2000 generations. In this case the total power consumption was reduced from 190 to 8 W (95.8 % reduction) while the percentage of satisfied users remained above 95 % during the whole optimization process.

5.1.2 Simulation of existing topology

The second experiment is performed over a real map. The experiment assumes 137 users located on roads, villages and public transport stations. In this case the base stations do not form a grid-like topology but they have been manually placed at strategic positions in order to be able to cover the whole area depending on the users' density. Figure 8 presents the resulting configuration that the algorithm proposes in order to use minimal power while retaining a SE over 1 bps/Hz for

Fig. 6 A grid-like topology with users placed on a ring formation



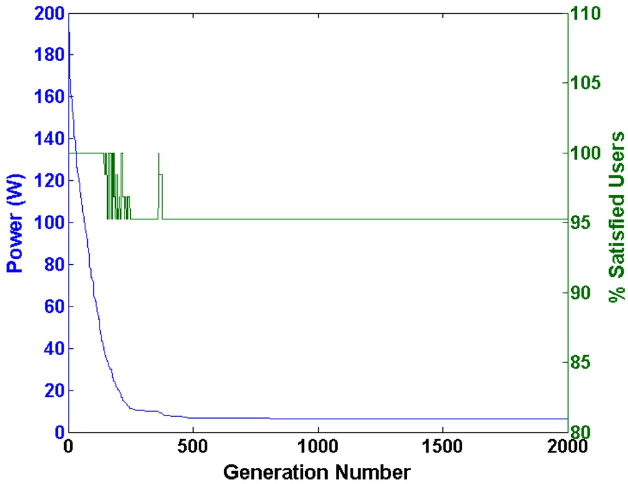


Fig. 7 Power consumption and percentage of satisfied users during the optimization process (63 users in total)

Fig. 8 The proposed deployment for the existing topology

at least 95 % of the users. The cells that participate in the MBSFN transmissions are marked with black, red, orange and yellow color in Fig. 8. This distinction targets at revealing the power level of the cells that are included in the MBSFN area. Black colored cells transmit at a lower power level while the yellow colored cells at a higher power level. Finally, the cyan cells are completely turned off since they are considered unnecessary by the algorithm.

The total power consumption and the percentage of satisfied users during the 2000 generations of the genetic algorithm can be seen in Fig. 9. At the end of the optimization process, the total power used by the network is 82.5 W and as a result the 95.62 % of the users experiences a SE over 1 bps/Hz. It is interesting to notice that during the first generations the power increases. This is caused because when the optimization starts the threshold for the satisfied users is not achieved and the algorithm increases the power in order to

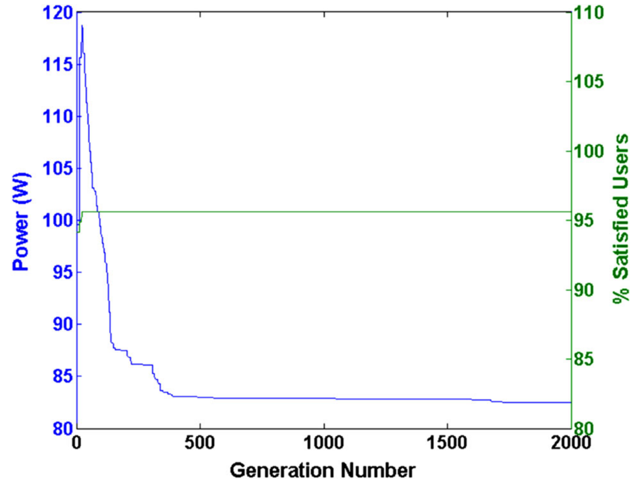


Fig. 9 Power consumption and percentage of satisfied users during the optimization process (137 users in total)

reach the threshold. After reaching the threshold, the algorithm starts optimizing the power consumption of the network.

5.2 Moving users scenarios

5.2.1 Vehicular users close to low-density urban area

The specific experiment investigates the case where a road with moving users passes by a low-density urban area that includes static users. According to the scenario a total of 36 base station antennae form a hexagonal grid with inter-site distance equal to 1,000 m. On the west side of the grid a static group of 100 mobile users are located in a square area with side equal to 1,000 m. A road with mobile users traveling at 50 km/h passes at a distance of 2,000 m from the center of the urban area. Every 20 s for the first 600 s a new mobile user enters the area from the north side of the road and stays visible for 382.6 s when he exits the simulated area from the south side of the road. Therefore the last user exits the simulated area at simulation time 982.6 s when the simulation finishes.

Figure 10 presents a snapshot of the simulated area during the experiment. The red lines connecting users to base stations show the antennae that each user votes for a power increase. According to the analysis presented in Sect. 4 the antennae with users voting for them have the tendency to increase their power more easily compared to those that no one votes for. On the other hand, the grey lines indicate that the user connected with them is mainly served by a remote antenna instead of an antenna that he votes for.

The total power consumption of the network and the percentage of satisfied users during the simulation is depicted in Fig. 11. It is clear that the algorithm manages to lower the power consumption of the algorithm during the exper-

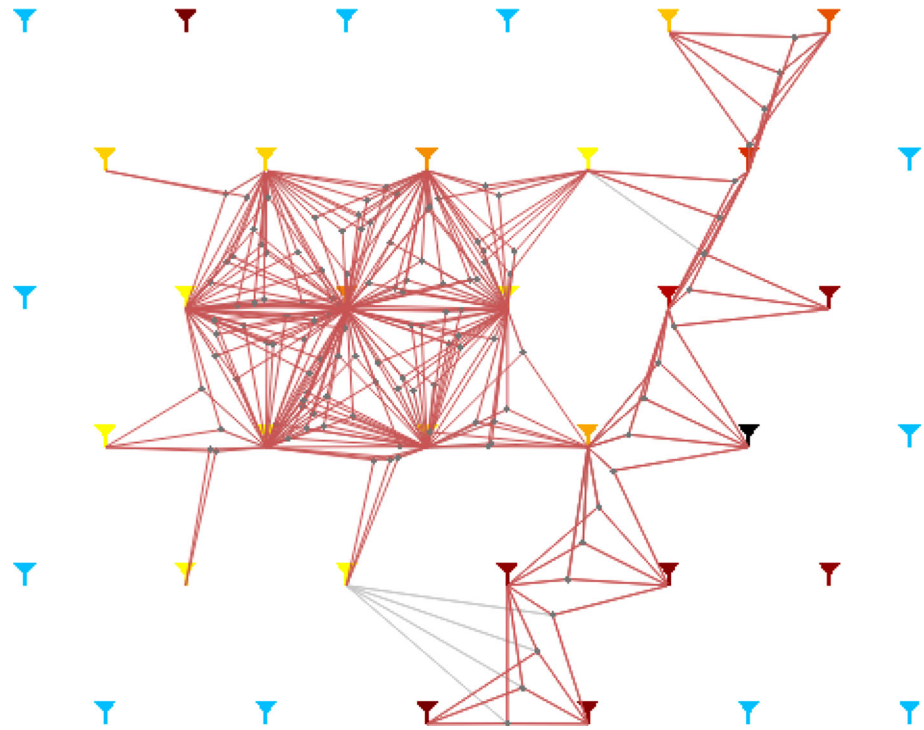


Fig. 10 A topology with users moving on a road near a populated area

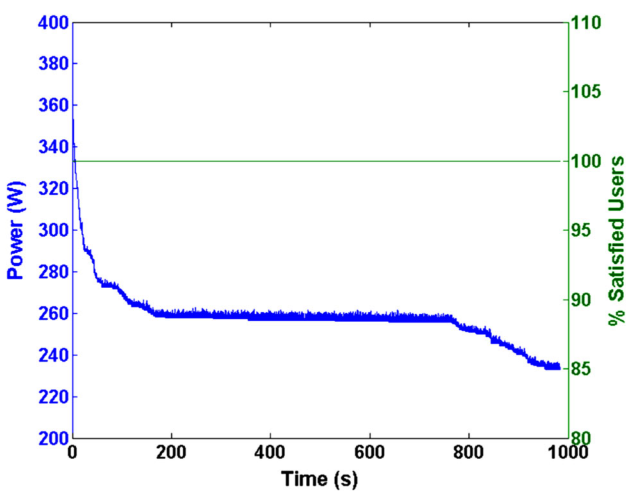


Fig. 11 Power consumption and percentage of satisfied users as a function of time for the "Vehicular users close to low-density urban area" experiment

iment. The initial state of the network is obviously using unnecessary power resources and the algorithm manages to reduce the total power in the first 200 s, ensuring simultaneously that all users will experience a SE over 1 bps/Hz. During the period 200–750 s the power consumption remains at a constant level (around 255 W) since a further reduction would result in decreasing the percentage of satisfied users. After simulation time 750 s there are no users entering the simulation area, while the users already traveling on the road start leaving the area. For that reason the algorithm manages to further reduce the power consumption by successively turning off the northern antennae that do not contain users. It is also important to notice that during the whole experiment the algorithm manages to keep all users satisfied since the green line is constantly at 1.

5.2.2 Random movement in confined area

In order to examine the system's behavior for a confined area where low mobility users pass through, in this experiment we define a 1 km^2 area containing 9 base station antennae uniformly placed on a hexagonal grid. Inside this area, a snapshot of which is presented in Fig. 12, 100 mobile users move randomly with speed 3.5 km/h. After 600 s of simulation the users start leaving the area and at simulation time 622 s the topology contains no users. However, the total duration of the experiment is 660 s in order to also examine how the algorithm behaves after the users have exited the area. The results are presented in Fig. 13. We can notice that the algorithm constantly lowers the power without leaving unsatisfied users. In detail the total power decreases from 90 to 63 W (30 % decrease) and when users start disappearing during the last seconds of the experiment it almost turns all MBSFN transmissions off reducing the total power to 25 W, 72.22 % decrease compared to the initial configuration. The decrease in power level is kept transparent to the users since during the experiment the percentage of satisfied users is constantly 1.

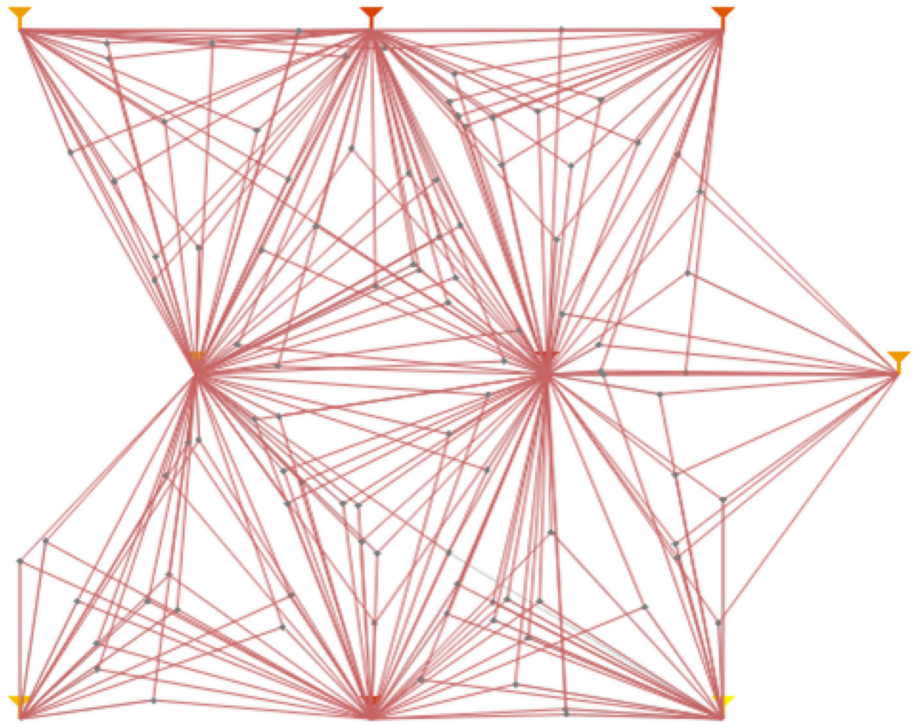


Fig. 12 A confined area with low mobility users

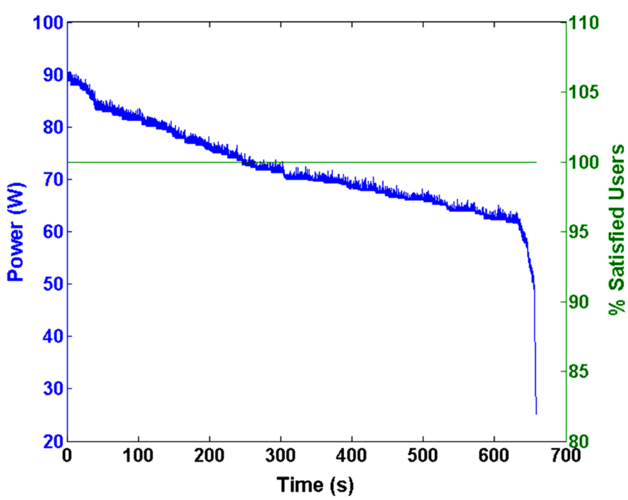


Fig. 13 Power consumption and percentage of satisfied users as a function of time for the "Random movement in confined area" experiment

5.2.3 Vehicular users in heavy traffic

The last experiment aims to examine the efficiency of the algorithm for users moving over a road. The road spans from the northern side of the topology to the southern side where the users leave the topology. The road has 3 lanes with each lane being at a distance of 4 m from its neighboring ones. According to the experiment, every 20 s for the first 600 s a new mobile user moves over the road from the northern side and exits the topology from the southern side after 382.6 s. Therefore the simulation finishes at simulation time 982.6 s when the last user exits the simulated area. Three successive snapshots of the network configuration are depicted in Figs. 14, 15 and 16. In these figures, the red colored cells correspond to the cells that transmit at a lower power level while the yellow colored cells at a higher power level. The cyan cells are completely turned off since they are considered unnecessary by the algorithm. In addition, the red lines indicate the antennae that each user votes for a power increase and the grey lines indicate that the user connected with them is mainly served by a remote antenna instead of an antenna that he votes for. Finally, Fig. 17 illustrates the results of the optimization process by revealing the total power consumption and the percentage of the satisfied users during the experiment.

During the first 10 s of the experiment, the algorithm rapidly decreases the power of most cells and the total power drops from 390 W to less than 70 W (see Fig. 17). The reason for this rapid decrease is that the initial state of the network is random and usually most cells transmit with higher power than necessary. During this time interval users start entering the network from the northern side and the three cells closest to the entry point tend to increase their power in order to serve those users (Fig. 14). These are the three yellow antennae in Fig. 14 that transmit at high power levels because they are voted by users to increase power.

As the first users move towards the southern side of the topology, they start voting for new cells to increase power; however users keep entering the simulation area and there-

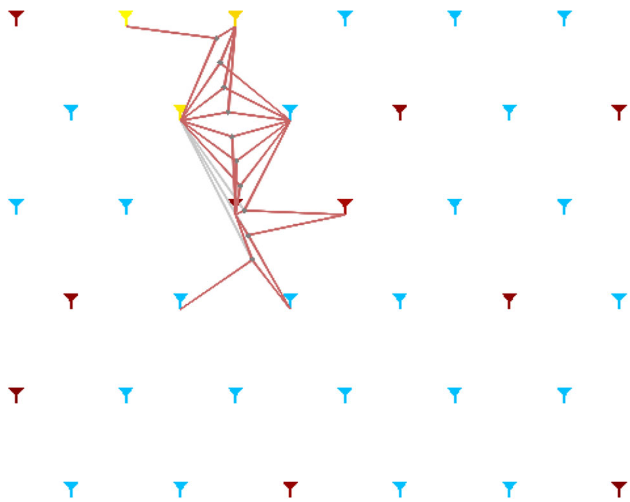


Fig. 14 Slow response when users leave the initial area (screenshot 1)

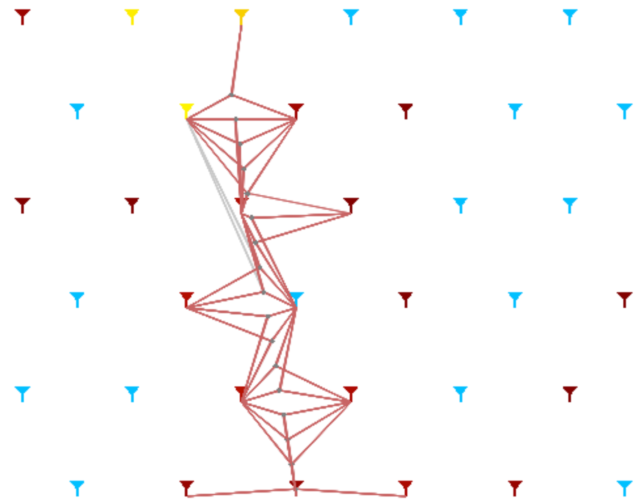


Fig. 16 Slow response when users leave the initial area (screenshot 3)

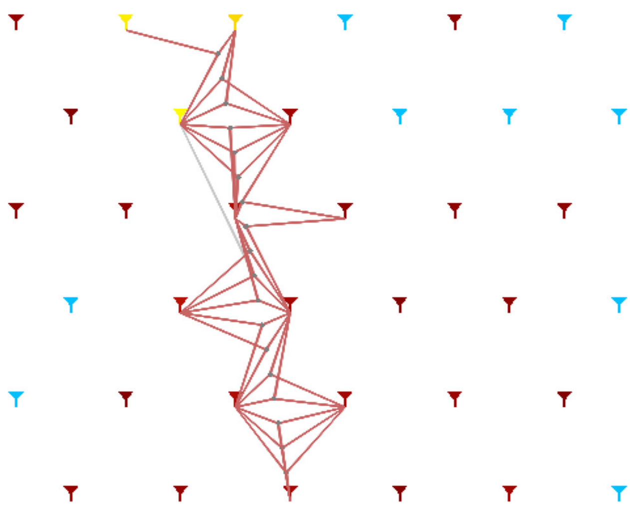


Fig. 15 Slow response when users leave the initial area (screenshot 2)

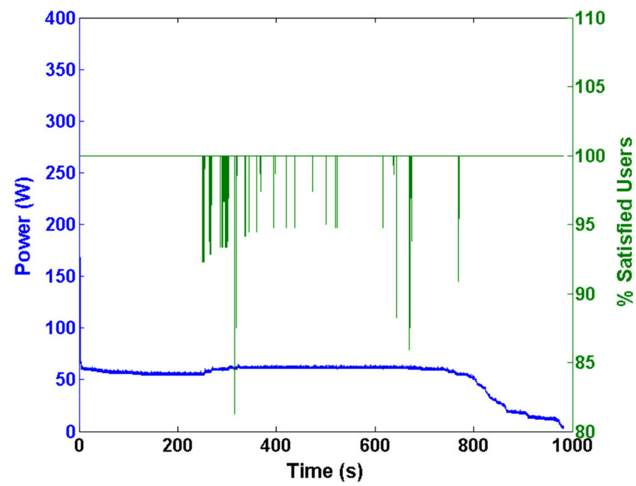


Fig. 17 Power consumption and percentage of satisfied users as a function of time for the "Vehicular users in heavy traffic" experiment

fore keep voting for the first three cells to increase their power as seen in Fig. 15. As a result, the first three antennae keep transmitting at a high power level; while the total consumption of the network increases since the cells in the middle and the southern side of the topology start increasing their power. This explains the small increment in the total power during the simulation time 260 s in Fig. 17.

In the last screenshot of the experiment presented in Fig. 16, the users have stopped entering the simulation area and successively move towards the southern side where they leave the topology. The initial three cells keep transmitting in high power levels even if no users vote for them, however, the total power consumption tends to decrease as depicted in Fig. 17 from 750 s until the end of the simulation.

Regarding the percentage of satisfied users, there were time instances that the algorithm could not reach the threshold and therefore more that 5 % of the users could not achieve the SE target of 1 bps/Hz. This mainly happens during the simulation time 220–700 s where the first users approach the middle and the southern side of the topology and start voting for the corresponding antennae to increase their power. As a result of the users' mobility and since the algorithm tries to keep the amount of satisfied users over 95 %, an immediate increase in the network power levels occurs, as depicted in Fig. 17 for the corresponding time period, and after a short time the 95 % threshold is achieved.

6 Conclusions

In this manuscript we proposed a system optimizer simulator that depending on the users' distribution defines the cells of the topology that will participate in the MBSFN transmissions and then adjusts transmission power of those cells. Main target of the optimizer is on the one hand to minimize the overall power resources and on the other hand to keep the percentage of the users that experience a SE of 1 bps/Hz above 95 %. It is based on a novel genetic algorithm that is designed so as to be resistant to entrapment in local optima and to make use of mutations over the previous solutions in order to optimize the power consumption. In order to make the simulator more user-friendly, we define an innovative network description language, namely the XTNDL language, as input that supports real coordinates for users and cells, allows arbitrary positioning for base stations and supports both static and moving users. This language was used for the description of mobile network's topology and the user mobility scenarios.

A dilemma we had during the design of our algorithm was how "smart" the optimization should be. When we used a completely "dumb", brute force approach where mutations were completely random, the algorithm was practically too slow to be used in real system deployments. On the other hand, creating a very "smart" algorithm with mutations being more deterministic and based on an analysis of the network might make the results skewed. In order to overcome the above problems, we used a partially "smart" algorithm which, while faster than brute force, still uses almost random mutations.

In order to evaluate the algorithm several experiments were conducted. The experiments included static and moving users so as to reveal the operation of the algorithm in both static and mobility scenarios. The main conclusion is that the algorithm succeeds to drastically reduce the network power consumption (up to 97.06 % reduction compared to the random initial configuration), increasing in that way the available power resources. In general, the overall power reduction is achieved by increasing the transmission power of the cells that contain MBSFN users to ensure the desired QoS target and, at the same time, by decreasing the power or completely turning off the power of the cells that do not constructively participate in MBSFN.

Besides the minimization of the power consumption, the experiments revealed that contrary to previous research works the use of assisting cells was never suggested by the genetic algorithm. The closest case to assisting cells was the case where cells had to serve only one user. This means that the algorithm avoids increasing the power of a cell that does not contain users and instead decides to serve the users using the closest cell to them.

7 Future work

There are several directions that could follow this work and where the scientific community may contribute to, since the implemented tool is publicly available at [11]. As a first step, our intention is to extend the XTNDL and use it in different simulators. Being an extension of Lua programming language, XTNDL could be easily embedded into existing simulators written in C/C++ or Java programming languages. A library to create agents that behave like humans by walking around or getting into a car and drive around could be created to provide even more realistic scenarios. These scenarios could be used to further examine the performance and the efficiency of the proposed algorithm. In order to simulate scenario with both pedestrian and vehicular users, XTNDL could also include small extensions to alter the path loss of each user individually based on their mobility profile. Extensions could also be used in order to further distinguish between indoors and outdoors users to make the simulations more realistic.

Regarding the algorithm's operation, future extensions could focus on the combination of MBSFN, point-to-multipoint and point-to-point transmissions to further decrease the power consumption of the network. The efficiency of point-to-multipoint and point-to-point transmissions could be investigated especially for those cells that their neighboring cells do not have users that want to receive the same multimedia data and therefore the use of MBSFN could be characterized as inefficient.

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