Optimization Method for the Joint Allocation of Modulation Schemes, Coding Rates, Resource Blocks and Power in Self-Organizing LTE Networks

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***Abstract*—This article investigates the problem of the allocation of modulation and coding, subcarriers and power to users in LTE. The proposed model achieves inter-cell interference mitigation through the dynamic and distributed self-organization of cells. Therefore, there is no need for any a prior frequency planning. Moreover, a two-level decomposition method able to find near optimal solutions is proposed to solve the optimization problem. Finally, simulation results show that compared to classic reuse schemes the proposed approach is able to pack more users into the same bandwidth, decreasing the probability of user outage.**

I. Introduction

In order to enhance the capacity of current cellular networks and satisfy the service demands of future user applications, both the mobile industry and the research community are working on the standardization of the fourth generation of radio technology referred to as Long Term Evolution (LTE). The downlink of LTE is based on Orthogonal Frequency Division Multiple Access (OFDMA), which provides both efficient multi-user access and intra-cell interference avoidance [1]. In LTE, the smallest radio resource unit that the scheduler can assign to a user is a Resource Block (RB) [2]. The RB contains 12 adjacent OFDM subcarriers with an inter-subcarrier spacing of $15\,kHz$. Each RB has a time slot duration of 1 ms, corresponding to 12 or 14 OFDM symbols. This depends on whether an extended or normal Cyclic Prefix (CP) is utilised. The assignment of RBs to users is done by the scheduler, which takes decisions for each subframe, i.e., every 1 ms. The main question to be addressed by the scheduler is how RBs are to be assigned to users and how much transmit power is to be applied to each RB. In addition, it should be noted that users may have distinct Quality of Service (QoS) requirements, and that the channel and interference conditions associated with each user may also vary in both time and frequency. Furthermore, a constraint in LTE downlink scheduling is that when a user is allocated to more than one RB, all these RBs must use the same Modulation and Coding Scheme (MCS). Nevertheless, different users connected to the same cell can be assigned to distinct MCSs [1]. This MCS constraint makes the problem of RB and power allocation for interference avoidance quite complex in Adaptive Modulation and Coding (AMC) networks such as LTE.

In literature, there are several categories of inter-cell interference mitigation approaches:

- At the low end of complexity, techniques based on Frequency Reuse Schemes (FRSs) and Fractional Frequency Reuse Schemes (FFRSs) do not involve any signaling between cells. However, due to their fixed allocation of bandwidth and power, they are not able to dynamically adapt themselves to the fluctuations of the network [3].
- At the high end of complexity, techniques based on coordinated scheduling within cell neighborhoods determine their bandwidth and power allocations. These schemes result in a better system performance, but they typically incur large signaling between cells and are difficult to implement (centralized / distributed approaches) [4], [5].

In order to cope with the disadvantages of centralized architectures, a completely different strategy that is based on a non-cooperative distributed approach is presented in [6]. The authors propose a network, where each sector constantly performs a selfish optimization of the assignment of its user packets to its existing resources. The authors show that aiming at minimizing the radiated power independently in each cell, the network settles into a stable frequency allocation pattern that changes dynamically according to sector traffic loads. Nevertheless, the AMC features of LTE are not considered, and thus it does not deal with the allocation of distinct MCSs.

This article presents a new model for the joint allocation of MCSs, RBs and power, taking the LTE MCS constraint introduced above into account.

This is done from a self-organizing perspective where each cell independently senses the radio channel and tunes its resource allocation in order to mitigate inter-cell interference. Distributed approaches like this facilitate cell deployments, since cells do not need to be connected to a central manager and there is no signalling between neighbouring base stations. Hence, they reduce latencies and avoid single points of failure. The main goal of the proposed optimization is to minimize the overall cell radiated power, while guaranteeing a minimum QoS level for each user. This paper also proposes an optimization solving tool able to find near optimum solutions at cell level in reasonable times.

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In this article, the terms eNodeB and base station are synonyms and refer to the equipment used to provide service in a given area. The terms cell and sector are also synonyms and refer to the eNodeB covered area or part of it.

TABLE I
MCS (MODULATION AND CODING SCHEMES) [7]

MCS	Modulation	Code Rate	SINR threshold $[dB]$	Efficiency $[bits/symbol]$
MCS1	QPSK	1/12	-6.50	0.15
MCS2	QPSK	1/9	-4.00	0.23
MCS3	QPSK	1/6	-2.60	0.38
MCS4	QPSK	1/3	-1.00	0.60
MCS5	QPSK	1/2	1.00	0.88
MCS6	QPSK	3/5	3.00	1.18
MCS7	16QAM	1/3	6.60	1.48
MCS8	16QAM	1/2	10.00	1.91
MCS9	16QAM	3/5	11.40	2.41
MCS10	64QAM	1/2	11.80	2.73
MCS11	64QAM	1/2	13.00	3.32
MCS12	64QAM	3/5	13.80	3.90
MCS13	64QAM	3/4	15.60	4.52
MCS14	64QAM	5/6	16.80	5.12
MCS15	64QAM	11/12	17.60	5.55

II. PRELIMINARIES

A. Network definition

Let us define an LTE macrocell network as a set of:

- macrocells $\mathcal{M} = \{M_1, ..., M_m, M_n, ..., M_M\}$,
- users per macrocell $\mathcal{U} = \{UE_1, ..., UE_u, ..., UE_U\}$,
- RBs $\mathcal{K} = \{1, ..., k, ..., K\}$,
- MCSs $\mathcal{R} = \{1, ..., r, ..., R\}$ (Table I).

B. Signal quality

Assuming that all subcarriers within a RB experience the very same channel conditions, the Signal to Interference plus Noise Ratio (SINR) $\gamma_{u,k}$ of user u in RB k is modelled as:

$$\gamma_{u,k} = \frac{P^m_{u,k} \cdot \Gamma_{m,u}}{w_{u,k} + \sigma^2} = \frac{P^m_{u,k} \cdot \Gamma_{m,u}}{\sum_{m'=1,m'\neq m}^{M} P^{m'}_{u',k} \cdot \Gamma_{m',u} + \sigma^2} \tag{1}$$

where $P^m_{u,k}$ denotes the power applied by M_m in each one of the subcarriers of RB k, in which user u is allocated. $\Gamma_{m,u}$ is the channel gain between macrocell M_m and user u. $w_{u,k}$ represents the received signal strength, i.e., interference, suffered by user u in RB k. Finally, σ is the noise density.

C. User capacity

The bit rate $BR_{u,r,k}$ as well as the throughput $TP_{u,r,k}$ of user u in RB k when using MCS r are modeled as:

$$BR_{u,r,k} = \Theta \cdot \mathit{eff}_r = \frac{SC_{ofdm} \cdot SY_{ofdm}}{T_{subframe}} \cdot \mathit{eff}_r \tag{2}$$

$$TP_{u,r,k} = BR_{u,r,k} \cdot (1 - BLER(r, \gamma_{u,k})) \tag{3}$$

where Θ is a fix parameter that depends on network configuration, being SC_{ofdm} and SY_{ofdm} the number of data subcarriers (frequency) and symbols (time) per RB, respectively, and $T_{subframe}$ is the RB duration in time units. In addition, eff_r is the efficiency ($bits\,/\,symbol$) of the selected MCS r, while $BLER(r, \gamma_{u,k})$ indicates the BLock Error Rate (BLER) suffered by RB k, which is a function of both r and $\gamma_{u,k}$.

D. Channel Quality Indication

In LTE, end-user u feeds back frequently (every $T_{u,cqi}$) a Channel Quality Identifier (CQI) CQI_u to its server M_m to report its channel conditions. In this case, wideband CQIs indicating the RSS $w_{u,k}$ of the interference suffered by user u in all RBs $\mathcal{K}$ are utilised [1], i.e., a user reports K values.

III. BASIS OF OUR RESOURCE ALLOCATION SCHEME

The main idea of our algorithm is that each macrocell M_m, using the optimization procedure presented in the next section, **independently** updates the MCS, RB and power allocation of its users according to the CQIs received from all of them. This updating event takes place after a random uniformly distributed time interval between 1 and $T_{m,up}$ time units after its last self-organization. In this way, the probability of many cells changing their allocation at the same time is reduced. Therefore, cells can assume that neighbouring cells will not vary their assignments while they carry out their optimisation.

The aim of the optimization process is to assign MCS, RBs and power to users in a cell, while minimizing the sum of the allocated power to all its RBs. The reasons why minimizing the sum of the transmitted power is a good cost function are:

1) A cell that aims at minimizing its transmitted power allocates less power to those users that are closer to the base station or have smaller throughput requirements. Like this and according to [8], interference is mitigated.
2) Minimizing the radiated power independently in each cell leads the system to self-organize into an stable frequency reuse pattern [6], hence avoiding the need for central coordinators and single points of failure, while reducing operator expenses and improving scalability.
3) Minimizing the radiated power leads to choosing those RBs for transmission that have the least interference. Note that a cell that targets at minimising its own radiated power tries to use those RBs that are not being used by neighboring cells because less power is needed in a non-interfered/faded RB to achieve a targeted SINR.

Thus, it is expected that the proposed self-organization of MCS, RBs and power in this manuscript tends to use as many RBs as possible (increasing RB use), each one of them with the least possible transmission power (decreasing interference), which leads to using lower MCSs. Note that a lower MCS is also more robust to channel variations, since it tolerates better SINR variations in terms of BLER. This will do the network more robust against unplanned traffic and channel fluctuations.

IV. THE RESOURCE ALLOCATION PROBLEM

This section defines our model for the MCS, RB and power assignment in macrocell M_m, i.e., an optimization problem called Resource Allocation Problem (RAP).

First of all, note that the power $P^m_{u,k,r}$ that macrocell M_m must allocate to all subcarriers of RB k assigned to user u in the downlink to achieve the SINR threshold γ_r of MCS r is:

$$P^m_{u,k,r} = \gamma_r \cdot \frac{w_{u,k} + \sigma^2}{\Gamma_{m,u}} \tag{4}$$

where all these variables are known by M_m (equation (1)). However, let us recall that $w_{u,k}$ represents the sum of the inter-cell interference suffered by user u in RB k, whereas $\Gamma_{m,u}$ is the channel gain between macrocell M_m and user u. $w_{u,k}$ and $\Gamma_{m,u}$ are known by M_m due to CQIs (Section II-D).

The optimization problem of the joint MCS, RB and power allocation in macrocell M_m can be formulated as the following integer linear problem:

$$\min_{\chi_{u,k,r}} \sum_{u=1}^{U} \sum_{k=1}^{K} \sum_{r=1}^{R} P^m_{u,k,r} \cdot \chi_{u,k,r} \tag{5a}$$

subject to:
$$\sum_{u=1}^{U}\sum_{r=1}^{R}\chi_{u,k,r} \leq 1 \qquad \forall k \qquad (5b)$$
$$\sum_{r=1}^{R}\rho_{u,r} \leq 1 \qquad \forall u \qquad (5c)$$
$$\chi_{u,k,r} \leq \rho_{u,r} \qquad \forall u,k,r \qquad (5d)$$
$$\sum_{k=1}^{K}\sum_{r=1}^{R}\Theta \cdot \mathit{eff}_r \cdot \chi_{u,k,r} \geq TP_u^{req} \qquad \forall u \qquad (5e)$$
$$\rho_{u,r} \in \{0,1\} \qquad \forall u,r \qquad (5f)$$
$$\chi_{u,k,r} \in \{0,1\} \qquad \forall u,k,r \qquad (5g)$$

where $P^m_{u,k,r}$ has already been introduce in equation (4). In this case, $\chi_{u,k,r}$ (5g) is a decision binary variable that is equal to 1 if user u uses MCS r in RB k, or 0 otherwise. Furthermore, $\rho_{u,r}$ (5f) is a decision binary variable that is equal to 1 if user u makes use of MCS r, or 0 otherwise. Constraint (5b) makes sure that RB k is only assigned to at most one user u, and constraints (5c) and (5d) together guarantee that each user is allocated to at most one MCS. Finally, constraint (5e) makes sure that each user u achieves its throughput demands TP_u^{req}.

V. The RB and power allocation subproblem

This section discusses an important subproblem of RAP referred to as RB and Power Allocation subProblem (RPAP) that happens when the MCS of each user is known a priori.

An efficient solution to this subproblem can be utilized as a low latency RB and power allocation scheme, and also as a sub-routine in order to solve the presented RAP problem (this is shown in Section VI).

Assuming that a MCS r_u has been selected for each user u, i.e., $\rho_{u,r}\forall u\forall r$ is known and fixed a priori as part of the input, the whole optimization problem transforms to an easier form.

Clearly, the used MCS r_u determines the number D_u of RBs needed for satisfying the throughput requirement TP_u^{req} of user u. Namely,

$$D_u := \left\lceil \frac{TP_u^{req}}{\sum_{r=1}^{R}(\Theta \cdot \mathit{eff}_r + Q)\cdot \rho_{u,r}} \right\rceil = \left\lceil \frac{TP_u^{req}}{\Theta \cdot \mathit{eff}_{r_u} + Q} \right\rceil \qquad (6)$$

where Q is a protection margin used to compensate the throughput loss due to BLER. The scheduler will also derive TP_u^{req} based on the QoS requirement of the user connection.

In addition, let us introduce the binary decision variable $\phi_{u,k}$, which indicates whether user u makes use of RB k, i.e.,

$$\phi_{u,k} := \sum_{r=1}^{R}\chi_{u,k,r} \qquad (7)$$

Substituting them into (5a)-(5g), we obtain the following RB and power allocation problem.

$$f(s) = \min_{\phi_{u,k}} \sum_{u=1}^{U}\sum_{k=1}^{K} P^m_{u,k,r_u}\cdot \phi_{u,k} \qquad (5a^*)$$

subject to:
$$\sum_{u=1}^{U}\phi_{u,k} \leq 1 \qquad \forall k \qquad (5b^*)$$
$$\sum_{k=1}^{K}\phi_{u,k} = D_u \qquad \forall u \qquad (5e^*)$$
$$\phi_{u,k} \in \{0,1\} \qquad \forall u,k \qquad (5g^*)$$

Let us note that due to the totally unimodular property [9] of the matrix of constraints $\phi_{u,k}$, the minimum of RPAP can always be selected to be integral.

Hence, the integrality constraint (5g*) can be replaced by

$$\phi_{u,k} \geq 0 \qquad \forall u,k, \qquad (5g^{**})$$

As a result, this formulation is now efficiently solvable by a general purpose Linear Programming (LP) solving package.

A. Solving RPAP optimally

The following observation makes possible to solve RPAP up to the optimality even more efficiently.

Claim 1. *Let us define the following* network flow *problem [10] with vertex set*

$$V := \mathcal{U} \cup \mathcal{K} \cup \{s,t\}, \qquad (8a)$$

edge set

$$E := \{(su) : u \in \mathcal{U}\} \cup \{(uk) : u \in \mathcal{U}, k \in \mathcal{K}\} \cup \{(kt) : k \in \mathcal{K}\}, \qquad (8b)$$

capacity function

$$cap(ab) := \begin{cases} D_b, & \textit{if } a = s, b \in \mathcal{U} \\ 1 & \textit{otherwise,} \end{cases} \qquad (8c)$$

and cost function

$$cost(uk) := \begin{cases} P^m_{u,k,r_u}, & \textit{if } u \in \mathcal{U}, k \in \mathcal{K} \\ 0 & \textit{otherwise.} \end{cases} \qquad (8d)$$

Then, a minimal cost network flow of value $\sum_{u\in\mathcal{U}} D_u$ will provide an optimal solution to RPAP.

In order to solve this problem, the *network simplex* algorithm [11] implemented in the LEMON library [12] has been used for our experimental evaluation.

VI. Solving the resource assignment problem

In this section, a metaheuristic based approach is proposed in order to solve the MCS, RB and power assignment problem. The key idea behind this approach is that a metaheuristic can be used to search over the MCS allocation solution space Ω. Meanwhile, for each MCS assignment, the optimal RB and power allocation can be derived in short times solving RPAP.

A Tabu Search (TS) metaheuristic that can be directly used to solve this problem in online scenarios is depicted in Alg. 1. Due to the lack of space, and because TS is very well-known within the optimization community, we will briefly describe it.

Vector s of size U indicates the MCS selected for each user u connected to macrocell M_m. Then, solving problem RPAP, the RB and power assignment associated to s is calculated. The quality of the MCS assignment s is evaluated according to the cost $f(s)$ of the RB and power allocation found by the subroutine, i.e., equation (5a*). Following this procedure and employing TS, different MCS assignments s can be tested in a sophisticated way in order to find a good solution $\rho_{u,r}\forall u\forall r$ in the MCS solution space Ω.

Moreover, let us note that in order to avoid frequent reassignments in macrocell M_m, a new assignment is loaded in macrocell M_m only if it provides a significant improvement. This improvement is measured over the previous cost function. In our case, new solutions must be 5% better than the existing. This helps to increase network stability and avoid ping-poning.

Algorithm 1 Tabu search algorithm

$s = s_0$; $f_s = f(s)$ {Initial solution}
$s_{best} = s$; $f_{best} = f_s$ {Initialize best solution}
$tabu = [\,]$ {Initialize tabu list}
$iter = 0$ {Initialize iteration counter}
while $iter < iter_{max}$ **do**
  $iter = iter + 1$
  $neigh = 0$ {Initialize checked neighbor counter}
  s_{best}^{neigh}; $f_{best}^{neigh} = 999999$ {Best neighbor}
  while $neigh < |\mathcal{N}|$ **do**
    $neigh = neigh + 1$
    $s' = neighbor(s)$ {Select a neighbor}
    $f_{s'} = f(s')$ {Compute its cost (solve RPAP)}
    {Check constraints}
    if $needed\_RBs(s') > K$ **or** $f'_s > P_m^{total}$ **then**
      continue
    end if
    {Is this the best solution so far?}
    if $f_{s'} < f_{best}$ **then**
      $s_{best} = s'$; $f_{best} = f_{s'}$ {Yes, save it}
      $s_{best}^{neigh} = s'$; $f_{best}^{neigh} = f_{s'}$ {Also the best neighbor}
      break {Stop looking for neighbors}
    end if
    {Is this movement forbidden?}
    if $movement(s, s')$ **in** $tabu$ **then**
      continue {Yes, skip it}
    end if
    {Is this the best neighbor?}
    if $f_{s'} < f_{best}^{neigh}$ **then**
      $s_{best}^{neigh} = s'$; $f_{best}^{neigh} = f_{best}^{neigh}$ {Yes, save it}
    end if
  end while
  $m = movement(s, s_{best}^{neigh})$
  $s = s_{best}^{neigh}$; $f_{best} = f_{best}^{neigh}$ {Move to best neighbor}
  $tabu = tabu + [m]$ {Add movement to tabu list}
  $update(tabu)$ {Remove too old entries}
end while

TABLE II
SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
#eNodeBs	19	BS Cable Loss	3 dB
Sectors per eNodeB	3	UE Ant. Gain	0 dBi
Site-to-site distance	500 m	UE Ant. Pattern	Omni
Carrier Frequency	2.0 GHz	UE Ant. Height	1.5 m
Channel Bandwidth	1.25 MHz	UE Noise Figure	9 dB
Frame Duration	1 ms	UE Body Loss	0 dB
RBs	12	Type of Service	Full buffer
OFDM data symbols	11	Min Service BR	250 kbps
BS Tx Power	43 dBm	Shadowing s.d.	8 dB
BS Ant. Base Gain	14 dBi	Path Loss Model	Note 2
BS Ant. Pattern	Note 1	Users number	12 per cell
BS Ant. Height	30 m	User distribution	Uniform
BS Ant. Tilt	8	Mean Holding Time	90 s
BS Noise Figure	5 dB	Min. dist. UE to BS	35 m

Note 1. $A(\theta) = -min[12\frac{\theta}{\theta_{3dB}}, A_m]$, $\theta_{3dB} = 70$, $A_m = 20\,dB$
Note 2. $L = I + 37.6 \cdot log_{10}(R)$, R in kilometers, $I = 128.1$ for $2\,GHz$

VII. Performance Evaluation

The scenario used is an hexagonal LTE network composed of 19 tri-sectored eNodeBs deployed over an area of $9\,km^2$. Each sector contains an average of 12 static user terminals. Since the network has 12 RBs this is a 100% network load. Users are uniformly distributed within the sector boundaries. A user holds in the network for a given time dictated by an exponential distribution of mean μ_p, and then it disconnects. When a user disconnects, a new one appears in a new position. A full buffer model is used to simulate the traffic of users. Furthermore, all users have a throughput demand of 250 kbps. Users incur outage if they cannot transmit at a throughput larger than their demand TP_u^{req} for a period longer than 9 s. Finally, let us note that users feed back CQIs at a constant frequency of $T_{u,cqi} = 8$ ms. This is sufficient to deal with the channel coherence time at user speeds up to 16 Km/h [13]. Path losses were modeled according to Note 1 in Table II, and slow fading was considered using a log-normal shadowing with a standard deviation of 8 dB. Moreover, subframe errors were modeled based on BLER look-up-tables taken from [7].

In this case, 10 min of network functioning were simulated. It is to be noted that in order to avoid border effects, statistics, i.e., samples, are collected from the central eNodeB and the first tier of interfering eNodeBs, but not from the second tier.

A. Optimization Performance

In order to compare the performance of our optimisation approach to that of an Integer Linear Programming (ILP) solver, we extracted 100 problem instances from our simulations. The ILP solver used for solving (5) was CPLEX 9.130 [14].

The average running time of the ILP solver was 346.21 s, while that of our two-level optimization approach was 0.49 s. Furthermore, on average, the total power requirement of the solution provided by our two-level optimization approach was 6.37 % higher than the optimal one.

These results show that our two-level optimization method provides a notable running time improvement over ILP solvers with a slight loss in solution quality.

When utilising network simplex, the average running time over one million different RB and power allocations (RPAP) in different sectors was estimated to be by around 0.29 ms. As a result, let us conclude that since RPAP can be solved faster than the maximum feedback frequency in LTE: 2 ms [1], thus it can be used as a way of 'fighting' fading fluctuations. In addition, the RAP can be solved fast enough (every 0.50 s) to adapt users MCSs to their path loss changes due to mobility.

B. System-level Performance

First of all, note that when the proposed self-organizing is used, each sector independently performs a RB and power assignment (RPAP) at a regular time interval of 100 ms. Moreover, each sector also performs a MCS, RB and power assignment (RAP) after a random time interval uniformly distributed between 0.5 s and $T_{m,up} = 1$ s after its previous MCS, RB and power allocation.

Two FRSs are used for comparison: reuse 1 and 3 [15]. When using *reuse 1*, all cells can access all available RBs. When using *reuse 3*, the spectrum is divided in 3 segments, and different segments are assigned to the cells of an eNodeB. In both cases, the power is uniformly distributed between subcarriers. This is a common approach in literature when devising Dynamic Spectrum Assignment (DSA) schemes [16]. We name this approach as Uniform Power Distribution (UPD).

When running FRSs, a radio resource management procedure is also carried out at a regular time interval of 0.50 s. In both cases, reuse 1 and 3, sectors allocate RBs according

The computer used for this simulation contained an AMD Opteron 275 running at $2.2\,GHz$ with $16\,GB$ of RAM.

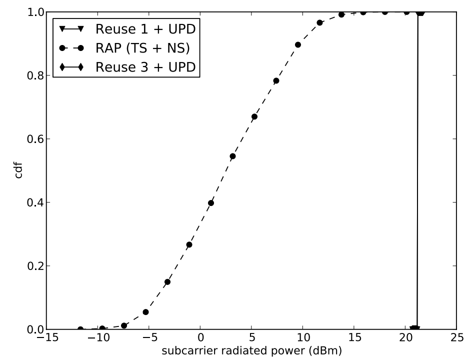

Fig. 1. CDF of the power applied (dBm) to RBs during the simulation.

TABLE III
SIMULATION RESULTS: USER STATUS

Technique	Reuse 1 + UPD	Reuse 3 + UPD	RAP
Users	1758	1758	1758
Outage	412	1195	82
Avrg. Sum TP [Mbps]	47.79	21.00	54.46
Avrg. Sector UE	194.79	84	241.07

to the model presented in [17], whose target is to minimise the sum of the interference suffered by all users of the sector. Let us also note that the LTE MCS constraint is respected, and all RBs assigned to a user have always the same MCS: The user MCS is selected according to the SINR of its RB in worst conditions, lowest SINR.

Figure 1 shows the Cumulative Distribution Function (CDF) of the power applied to the subcarriers during the simulation. When using reuse 1 and 3 the power applied to each RB is fixed and does not vary according to interference/load fluctuations. On the contrary, when using the proposed self-organizing approach not only the power applied to each RB changes depending on such conditions, but it is also smaller. Like this, interference towards neighboring cells is mitigated.

Table III shows the total number and percentage of incurred outages, the average number of users connected per cell and the average network throughput.

Table III indicates that reuse 3 produces the largest number of outages (67.97%) compared to the other two approaches. This is because the cell bandwidth is trimmed by a factor of 3. With regard to our reuse 1, it provides a larger cell bandwidth, however it still results in many dropped (23.44%) sessions. Because the cells are fully loaded and since a UPD is utilised, the scheduler of a cell cannot 'find' RBs that are not used in neighbouring cells, thus increasing the RB collision probability and reducing the average signal quality of all connected users. Therefore, a larger number of RBs is needed for each user in order to maintain their throughput requirement, i.e., TP_u^{req}. As a result, when the sector load is high, it is difficult to admit new users or if the interference coming from the neighboring cells suddenly increases, it is impossible to meet their demand.

On the contrary, in this scenario, the proposed approach is able to significantly mitigate outages (4.66 %) and increase throughput. This is due to its ability to minimize inter-cell interference and adapt the MCS, RB and power assignment of the cells to their neighborhood conditions. The proposed approach is able to achieve a high degree of interference avoidance through power minimisation and RB allocation. Allocating less power to those users that are close to the base station or enjoy good channel conditions reduces interference and allows neighbouring cell to find allocation opportunities. In this way, more users can access the same pool of resources.

VIII. CONCLUSION AND FURTHER WORK

This research article has investigated the problem of the allocation of MCS, RB and power to users in LTE networks. In our model, each cell selfishly pursue its own objective therefore leading to a completely decentralised architecture. In our case, the presented two-level optimization approach had been shown to be able to achieve near optimal solutions in affordable times. Simulations has also shown that this algorithm significantly improves network capacity in terms of user connections and throughput compared to classic FRSs. Future work will analyse the convergence of this algorithm through theoretical analysis, and compare its performance to that of centralised schemes designed to find global optimums.

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