A Centralised Approach to Power On-Off Optimisation for Heterogeneous Networks

Georgios P. Koudouridis, Gao Hui, Peter Legg
Radio Network Technology Research
Huawei Technologies Sweden, R&D Center
Kista, Sweden

Abstract— **The design of centralized algorithms and techniques allowing for an efficient utilisation of infrastructure in terms of energy consumption is one of the key challenges in heterogeneous networks (HetNets). In this study the energy efficiency in the HetNet scenario is formulated as an optimisation problem and an iterative improvement algorithmic approach to power on-off of network cells is devised and evaluated. The algorithm is based on the simulated annealing search approach and the obtained network configuration solutions are compared to a baseline configuration scenario where all cells are powered on. The optimization search is guided by an objective function which is defined on outage throughput and energy efficiency. Simulation results show that significant energy reductions gains can be achieved by switching off macro cells and with no loss of the cell edge user throughput. In some scenarios the algorithm generates solutions which considerably increase network throughput. The gains are more pronounced in configurations where pico cells are deployed at hot zones of user clusters.**

Keywords- energy savings; LTE; heterogeneous networks

I. INTRODUCTION

Cellular systems are designed for peak hour traffic despite the fact that the traffic activity in a certain area is high only during short periods of the day. Considering the traffic activity in a residential area, it is usually low during daytime when people have left homes for work while it increases in the evenings when people are at home. The opposite pattern prevails for the office area. In a heterogeneous network environment different infrastructures are differently utilised throughout the duration of a day, e.g., macro cells are serving traffic in a residential area during working hours while a vast amount of the traffic is carried by pico or femto cells during evenings and late hours. At the opposite end of the city in the working areas these indoor femto cells or outdoor pico cells that provide indoor coverage are not fully utilised at the end of business days or during evenings and nights. In all cases under-utilization of the radio infrastructure and radio resources is a waste of power and significant power savings could be achieved by reducing the number of radio resources that the network provides in time, space and frequency, e.g., by switching off a number of base stations at different tiers (micro, pico, femto etc.).

One of the simplest approaches to obtain energy efficiency is based on the activation of network resources on demand, thus avoiding to always power on all the resources that are necessary to serve the users during peak traffic periods [1]. This necessitates the implementation of a power on-off strategy that refers to the switching of radio infrastructure nodes and cells of a radio network. The radio network is a heterogeneous network (HetNet) consisting of sites with different power transmission, coverage and capacity profiles. One of the key optimisation problems in such HetNet scenario is to maximize or maintain user throughput and coverage at a minimum of energy consumption cost. As an attempt to solve the above problem we devise an iterative algorithm based on a simulated-annealing search. The algorithm is evaluated by means of simulations and results are compared to a reference scenario and discussed.

There is a considerable set of papers on energy savings in wireless networks. Some consider switching off a group of cells, e.g., [2][3], others focus on specific radio access technologies characteristics, e.g., UMTS [4] and/or use of different optimisation approach e.g., [5]. Compared to previous work, the proposed approach differs in two ways. First, it captures the trade-off between throughput and power consumption, and secondly it considers the details of switching on and off individual cells. More specifically, the outline of the paper is as follows: Section II introduces basic concepts of the system model, formalizes the problem and describes the algorithm. In Section III basic simulation parameters and assumptions are described, whilst simulation results are discussed in Section IV. Finally, conclusions are drawn in Section V.

II. CENTRALISED POWER ON-OFF OPTIMISATION

A. System Model

In this study, we consider a heterogeneous radio network consisting of a set of cells C, and a set of user mobiles M. Each mobile $m \in M$ is connected to a cell $c(m) \in C$, called the serving cell. A mobile m's serving cell is the cell with the maximum Reference Signal Received Power (RSRP), $p_{c,m}$ among all cells $c \in C$ in the network.

$$c(m) = \operatorname*{argmax}_{c \in C}\left(p_{c,m}\right) = \operatorname*{argmax}_{c \in C}\left(p_c g_{c,m}\right) \tag{1}$$

where p_c is the reference signal (RS) transmit power of cell c, and $g_{c,m}$ is the channel gain between cell c and mobile m. The transmit power p_c corresponds to the maximum transmit power of a cell c and its value depends whether cell c is a macro cell or a pico cell; hence the heterogeneous

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network. In this study we assume that the set of all cells is divided into two subsets, each subset corresponding to specific type of cell, a set of macro cells C_m and a set of pico cells C_p. Let $K = |C_m|$ denote the number of macro cells, $L = |C_p|$ denote the number of pico cells and $C_{tot} = |C|$ the total number of cells in the network. Let also $N = |M|$denote the total number of mobile users, and $N_c = |M_c|$ the number of mobiles connected to cell c. Clearly, $C = C_m \cup C_p$, $C_{tot} = K + L$, $N = \sum_{c \in C} N_c$ and $M = \bigcup_{c \in C} M_c$, where M_c is the set of all mobiles served by cell c.

The signal to interference and noise ratio (SINR) of mobile m is determined by RSRP and noise n as follows

$$\gamma_m = \frac{p_c g_{c(m),m}}{\sum_{c \neq c(m)} p_c g_{c,m} + n} \quad (2)$$

where $g_{c(m),m}$ denotes the path gain between the mobile m and its serving cell $c(m)$ whilst $g_{c,m}$, denotes the path gain between the mobile m and any interfering cell $c \neq c(m)$. All cells utilise the same frequency spectrum which is allocated to users in terms of Physical Resource Blocks (PRBs) as in orthogonal frequency division multiplexing access (OFDMA). Each resource block is defined in terms of a number of resource units in time, as number of symbols, and in frequency, as number of frequency subcarriers. Without loss of generality performance parameters and metrics are calculated on a per PRB basis. Full buffer traffic model and round-robin scheduling are assumed where we approximate throughput R_m of mobile m per PRB as a mapping function r_m of γ_m which is derived by link level simulations.

$$R_m = r_m(\gamma_m)\, h_{c(m)} \quad (3)$$

B. Problem Formulation and Concepts

At any time the configuration of a cell c may be in one of two possible states h_c: powered-on ($h_c = 1$) or powered-off ($h_c = 0$). Depending on the configuration state of each cell, the configuration of the entire heterogeneous network can be defined in terms of a transmit indicator vector $\boldsymbol{h}$ and a power transmit vector $\boldsymbol{p}$ as given by

$$\boldsymbol{h} = (h_1, h_2, \dots, h_K, h_{K+1}, \dots, h_{K+L}) \quad (4)$$

$$\boldsymbol{p} = (p_1, p_2, \dots, p_K, p_{K+1}, \dots, p_{K+L}) \quad (5)$$

where p_c and h_c are the power transmit and the power on/off state configuration of cell c respectively.. Here the transmit indicator vector $\boldsymbol{h}$ indicates the configuration of the network at any one time and constitutes the optimization variable of the system. That is, given the path gains, cells' transmit powers, and the noise, the goal is to find a solution that is optimal in terms of the mean cell edge user throughput O and the energy consumption rate E. The cell edge user throughput per PRB is defined as the 5th percentile (5%-*ile*) of the user throughput R, i.e., $O = R_{[(N+1)/20]th}$. The mean user throughput per PRB is defined by

$$\bar{R}_{user}(\boldsymbol{h}) = \frac{\sum_{m \in M} R_m h_{c(m)}}{N} \quad (6)$$

Similarly the mean cell throughput per PRB is defined as

$$\bar{R}_{cell}(\boldsymbol{h}) = \frac{1}{C_{tot}} \cdot \sum_{c \in C} \frac{\sum_{m \in M_c} R_m h_c}{N_c} \quad (7)$$

The Energy Consumption Ratio E of a configuration $\boldsymbol{h}$ is defined as the ratio in Joules/bit between the mean transmit power consumed (RF power) and the mean cell throughput

$$E(\boldsymbol{h}, \boldsymbol{p}) = \frac{\sum_{c \in C} h_c p_c}{\bar{R}_{cell}(\boldsymbol{h}) C_{tot}} \quad (8)$$

Cell edge user throughput and energy consumption ratio are combined into a single aggregate objective (utility) function $f(\boldsymbol{h}, \boldsymbol{p})$ in which the utility value of the current working configuration $\boldsymbol{h}_w$ is calculated relative to a baseline reference configuration $\boldsymbol{h}_r$ as the weighted sum

$$f(\boldsymbol{h}_w, \boldsymbol{p}_w) = \alpha \cdot \frac{O(\boldsymbol{h}_w)}{O(\boldsymbol{h}_r)} + (1 - \alpha) \cdot G(\boldsymbol{h}_w, \boldsymbol{p}_w) \quad (9)$$

where f corresponds to the objective function; coefficient α, $0 \le \alpha \le 1$ is a weight that corresponds to the significance of the terms. The first term is defined by the ratio of the outage (or cell edge) throughput of the current configuration $O(\boldsymbol{h}_w)$ over the outage throughput of the baseline configuration $O(\boldsymbol{h}_r)$. The second term, corresponds to the Energy Reduction Gain (ERG) G and is defined based on the ratio of the ECR of current configuration $E(\boldsymbol{h}_w, \boldsymbol{p}_w)$ over the ECR of the baseline configuration $E(\boldsymbol{h}_r, \boldsymbol{p}_r)$.

$$G(\boldsymbol{h}_w, \boldsymbol{p}_w) = 1 - \frac{E(\boldsymbol{h}_w, \boldsymbol{p}_w)}{E(\boldsymbol{h}_r, \boldsymbol{p}_r)} \quad (10)$$

Given the above metrics the optimization problem is to

$$max\ f(\boldsymbol{h}, \boldsymbol{p}) \quad (11)$$

subject to

$$\min_{\forall m \in M, \forall c(m) \in C} \left(p_c g_{c(m),m} \right) > \vartheta_{RSRP} \quad (12)$$

where ϑ_{RSRP} is a threshold value of the received signal strength that also determines the borders of a coverage area.

C. Optimisation Algorithm

Finding a solution that maximizes f can be practically performed by means of search based on an iterative improvement algorithm. The general idea is to start with a working configuration, for instance the baseline configuration, and generate new configurations which perform better in terms of the objective function f. The most common algorithm in this family is the hill-climbing search which is simply a loop that continuously moves in the direction of increasing utility value. It terminates when it reaches a peak where no "neighbour" configuration has a higher utility value. The main drawback of hill-climbing search is that, depending on its initial configuration, it can get stuck in local maxima (minima). Simulated annealing [6] is a variation of stochastic steepest ascent hill climbing, in which at the beginning of the process, the algorithm readily allows some more downhill movements while at the end this occurs less often. It is based on the annealing process used to temper or harden metals by heating them and the gradually cooling them. By doing so the algorithm allows exploration of the whole configuration space making the final solution insensitive to the initial configurations. Fig. 1 depicts the steps involved in the simulated annealing algorithm.

function SIMULATED-ANNEALING

returns a configuration vector $\boldsymbol{h}_w$ that maximizes the objective function f

input: K cells (network topology of M macros and L picos),

N dropped users

local variables: $\boldsymbol{h}_w$, current working configuration vector.

$\boldsymbol{h}_s$, highest successor configuration vector

T, a variable controlling the probability of accepting lower probability

$\boldsymbol{h}_w \leftarrow$ INITIAL-CONFIGURATION (K)

for $t \leftarrow 1$ to τ **do**

$T \leftarrow$ SCHEDULE (t, τ)

if $T = 0$ **then return** $\boldsymbol{h}_w$

$\boldsymbol{h}_s \leftarrow$ GENERATE_SUCCESSOR_CONFIGURATION ($\boldsymbol{h}_w$)

$\Delta f \leftarrow$ UTILITY ($\boldsymbol{h}_s$) - UTILITY ($\boldsymbol{h}_w$)

if $\Delta f > 0$ **then** $\boldsymbol{h}_w \leftarrow \boldsymbol{h}_s$

else $\boldsymbol{h}_w \leftarrow \boldsymbol{h}_s$ only with probability $e^{-\Delta f/kT}$

end

Figure 1. A pseudocode of the simulated annealing search algorithm [6]

Initially, the working configuration $\boldsymbol{h}_w$ is set to the baseline reference configuration vector $\boldsymbol{h}_r$, although any configuration vector generated in random would do (INITIAL_CONFIGURATION). At each iteration step the rate at which the temperature is lowered, is determined (SCHEDULE), and a new configuration vector $\boldsymbol{h}_s$ from current configuration vector $\boldsymbol{h}_w$ is generated (GENERATE_SUCCESSOR_CONFIGURATION), and evaluated (UTILITY). Within the loop the value of T is expressed as a function of the iteration steps (or time), by $T = 1 - {}^{t}/_{\tau}$. T goes to zero as the iteration t approaches the τth iteration step. It can be proven that if T decreases slowly enough then the simulated annealing algorithm will find a global optimum with probability approaching to one.

The "successor vector" is the configuration vector resulting from one iteration step of the algorithm. The search algorithms differ in their way to produce a successor state. Generally, the successor function has to be sufficiently conservative to preserve significant "good" portions of the current solution and liberal enough to allow the state space to be preserved without degenerating into a random walk. Here the successor function returns the configuration $\boldsymbol{h_s}$ with the highest utility value f among the set of all configurations having a Euclidean distance from the current working configuration $\boldsymbol{h_w}$ equal to one. If the new configuration vector $\boldsymbol{h_s}$ is better than $\boldsymbol{h_w}$ it is kept ($\Delta f > 0$); otherwise it is kept with some probability proportional to the temperature T (probability = $e^{-\Delta f/kT}$). Without loss of generality and in order to simplify the probability to select a worse utility scoring configuration vector the factor k , which describes the correspondence between the units of f and the units of T, is eliminated by assuming $k = \Delta f$ at all times, thus, reducing the expression of the probability to the more deterministic form of $e^{-1/T}$.

TABLE I NETWORK AND SYSTEM CONFIGURATION PARAMETERS

Parameters		Values and Assumptions	
		Macro Cell	Pico Cell
HetNet deployment		Environment: Macro + outdoor pico	
Carrier Frequency / Bandwidth		2 GHz / 10 MHz, FDD	
Inter site distance		500 m	N/A
Macro Cellular layout		Hexagonal grid, 7 sites, 3 sectors per site, $K = 21$ macro cells in total	
Pico distribution		4 Picos / macro cell, uniformly, $L = 84$ pico cells in total (case 1 in table A.2.1.1.2-4 [7])	
UE distribution	Configuration1	25 UEs / macro cell, uniformly (case 1 in table A.2.1.1.2-4 [7])	
	Configuration4	20 UEs/macro cell, 10 UEs/pico cell, clusters (case 4 in table A.2.1.1.2-4 [7])	
Minimum distance		40 m among picos	10 m between UE and pico
		75 m between pico and macro	35 m between UE and macro eNB
Traffic model		Full buffer	
Scheduler		RR (static) – each UE attached to a cell gets an equal share of the 10MHz bandwidth	
Number of iterations, τ		200	
Throughput model		L2S curve with TU channel at 3km/h [8]	

TABLE II ANTENNA, POWER AND PROPAGATION PARAMETERS

Parameters	Values and Assumptions
TX power (Ptotal)	46 dBm /macro cell, 30 dBm /pico cell and 23dBm/user equipment
Antenna	2 TRXs per macro/pico cell DL 2×2 MIMO, UL 1×2 SIMO
Antenna gain (macro horizontal)	$A_H(\varphi) = -\min\left[12\left(\frac{\varphi}{\varphi_{3dB}}\right)^2, A_m\right]$ $\varphi_{3dB} = 70$ degrees, $A_m = 25$ dB
Antenna pattern (macro-vertical)	$A_V(\theta) = -\min\left[12\left(\frac{\theta - \theta_{etilt}}{\theta_{3dB}}\right)^2, SLA_V\right]$ $\theta_{3dB} = 10$ degrees, $SLA_V = 20$ dB
Antenna gain(pico)	$A(\phi) = 0$dB (omnidirectional)
Combining method in 3D antenna pattern	$A(\varphi,\theta) = -\min\{-[A_H(\varphi) + A_V(\theta)], A_m\}$
Antenna gain	14 dBi/macro cell, 5 dBi/pico cell , 0 dBi/user
Noise Figure	5 dB/cell, 9 dB/user
Distance-dependent path loss for macro to UE*3	L= 128.1+37.6log10(R) for 2 GHz, R in *km*
Distance-dependent path loss for pico to UE	L= 140.7+36.7log10(R) for 2 GHz, R in *km*
Lognormal Shadowing with standard deviation	8 dB for eNB to UE, 10 dB for pico to UE
Shadowing correlation	0.5 between macro sites, 1.0 between macro sectors, N/A between picos, 50m corr. distance

III. SIMULATION MODEL

A. Heterogeneous Network Model

The definition of heterogeneous networks and scenarios follows the HetNet scenario as described in 3GPP for LTE-A [7]. The network consists of a hexagonal grid of seven macro base station sites with 3-sectors (cells), each sector having four pico cells within its coverage area. Macro and pico cells share the same frequency band of 10 MHz. The power transmitted from a base station in a macro cell is 46 dBm

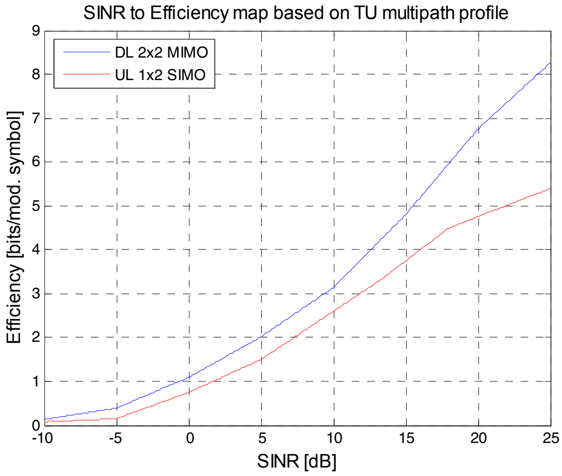


Figure 2. SINR to capacity mapping with TU multipath profile [8]

allowing an inter-node distance of 500 m up to few kilometres while the corresponding power emitted in a pico cell is 23 dBm with an inter-node distance of 100m to 300m. Pico cell equipment is of low cost, with no power control and omni-directional antennas. In 3GPP LTE-A standards and as defined in [7], two main deployment configurations are considered: *Configuration 1* and *4*. In *Configuration 1* a fixed number of users, or user equipments (UEs) in LTE parlance, and a fixed number of pico cells are uniformly and independently distributed within each macro cell. In *Configuration 4*, the user distribution is clustered in the sense that a fixed number of users are dropped within a pico cell's coverage area and the rest are uniformly dropped in the entire coverage area of the macro cell. The average user data rate R_m is a function of the average received SINR and is based on a SINR to Spectrum Efficiency (SE) mapping curve r_m similar to [8]. Fig. 2 shows the downlink (DL) 2x2 MIMO and uplink (UL) 1x2 SIMO SINR to capacity mapping curves for IID fading with typical urban (TU) multipath profile. The DL 2x2 MIMO efficiency curve is obtained based on link level simulations with wideband rank indicator (RI) and frequency selective channel quality indicator (CQI) and pre-coding matrix indicator (PMI) report with 5ms periodicity of report. The curve incorporates sub-band scheduling based on the reported CQI. These and other simulation parameters are summarized in tables I and II.

IV. Simulation Results

A. Simulation Assumptions

In the simulations the threshold value of the received signal strength is set to -120dBm ($\vartheta_{RSRP} = -120dBm$). This value is representative of a typical receiver sensitivity for an LTE handset device. Also users are not mobile, but rather static, therefore cells without any users are not included in the calculation, e.g. throughput calculation, interference calculation and ECR calculation. This has no impact on the throughput or the energy consumption. Empty cells are switched off at the end of the optimization to give the final count of cells that are on /off. Similarly, in the baseline configuration cells without users are switched off. In fact, simulation results indicate that even in the reference scenario, the number of empty pico cells is already significant; hence, some of the sites may be turned off.

B. Performance Metrics

The following performance metrics has been used for performance analysis.

1) UE throughput CDF: This is defined as the CDF for the throughput observed by each UE, on the downlink.

2) Cell mean throughput CDF: This is defined as the CDF for the mean throughput observed by each cell on the downlink.

3) Energy efficiency: The energy efficiency is expressed in terms of ECR and ERG, and at the network level is dependent on the number of cells that are powered on/off and the throughput as compared to the baseline scenario.

C. Simulation Results

Tables III and IV summarize the main metrics of the baseline and the optimized network using the simulated annealing algorithm. The maximum number of macro cells and pico cells that can be switched on is 21 and 84, respectively.

Configuration 1: This deployment configuration broadly reflects on a pico deployment with no planning. From the results, as shown in table III, cell edge user throughput increases as the coefficient increases since the first component in the utility function takes more weight, whilst the ERG falls. If cell edge throughput is not a major concern then the ECR

TABLE III. CONFIGURATION 1 –RESULTS SUMMARY

Coefficient α	#Cells ON Macro/Pico	Outage (%)	Mean UE throughput (Mbps)	Mean cell throughput (Mbps)	O (Mbps)	E(mW/Mbit/s)	Obj. function f	G(ERG)
N/A	21/ 41	0.00	1.68	14.24	0.22	19.87	0.00	NA
0	4 /62	0.14	1.91	15.22	0.08	4.40	0.78	0.78
0.25	5/ 67	0.09	1.80	13.12	0.19	5.63	0.76	0.72
0.5	14/ 53	0.00	1.85	14.47	0.21	12.59	0.67	0.37
0.75	19/ 44	0.00	1.70	14.15	0.23	17.96	0.83	0.10
1	19/ 43	0.00	1.65	13.96	0.23	18.47	1.06	0.07

TABLE IV. CONFIGURATION 4 –RESULTS SUMMARY

Coefficient α	#Cells ON Macro/Pico	Outage (%)	Mean UE throughput (Mbps)	Mean cell throughput (Mbps)	O (Mbps)	E(mW/Mbit/s)	Obj. function f	G(ERG)
N/A	21/ 64	0.00	0.90	13.31	0.12	15.91	0.00	NA
0	2/ 71	0.73	1.10	18.91	0.12	2.18	0.86	0.86
0.25	2/ 75	0.73	1.11	18.24	0.13	2.20	0.91	0.86
0.5	3/ 74	0.80	1.08	17.66	0.13	2.85	0.96	0.82
0.75	13/ 68	0.00	1.00	15.54	0.12	9.31	0.88	0.42
1	18/ 53	0.00	0.83	14.77	0.13	14.68	1.12	0.08

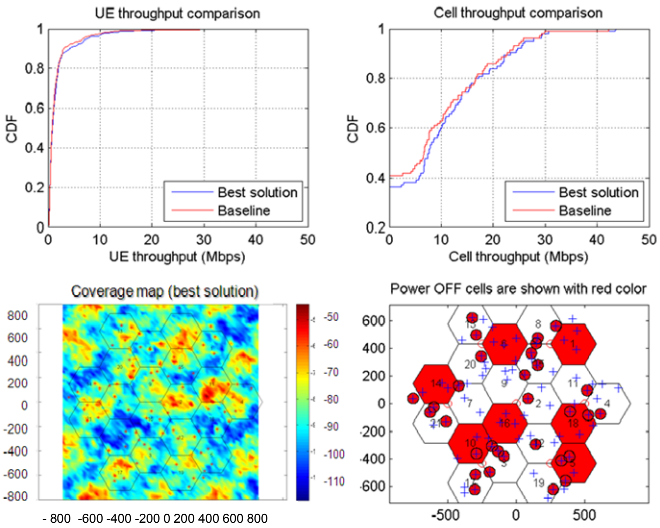
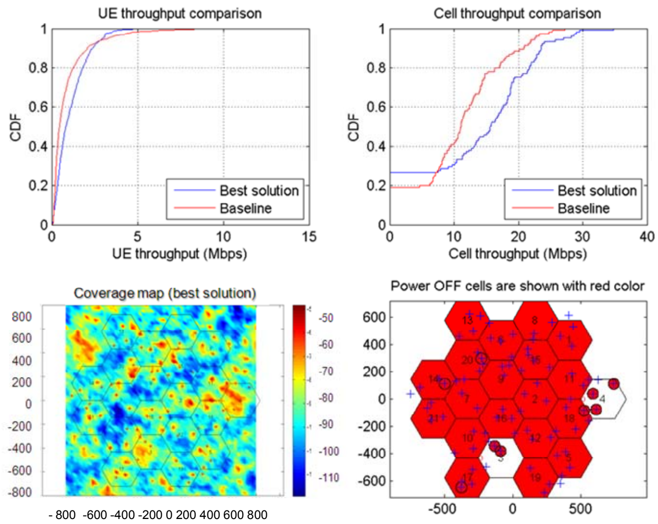


Figure 3. Simulation results for UE Configuration 1 and $\alpha = 0.75$



gure 4. Simulation results for UE Configuration 4 and $\alpha = 0.25$

can be significantly reduced using coefficient equal to zero – ERG is 0.78, so ECR is 0.22 times that of the baseline. Whilst there is a useful network throughput gain (13%), the power reduction is the main cause of the large ERG. If cell edge throughput is important, setting the coefficient to 0.5 gives similar cell edge throughput values as the baseline whilst achieving an ERG of 0.37 and an increase in network throughput (by 10%). The performance metrics of this scenario are depicted in Fig. 3.

When ERG is the only consideration, the algorithm switches off many macro cells but switches on a number of pico cells to maintain capacity. The macro power is forty times that of the pico cell. In fact, the capacity is greater than in the baseline (the mean UE throughput increases and the number of UEs is fixed). Since minimum RSRP is constrained, four macro cells are not switched off.

Configuration 4: As compared to Configuration 1, this configuration reflects on a scenario where pico cells are located at hot zones where user density is high. In the baseline the majority of pico cells are switched on. This is because many of the UEs are clustered around the pico cells, and there are more UEs in the network. Clearly the freedom to switch off cells diminishes as the network load increases. When the coefficient is set to zero, again, there is a large reduction in ECR, largely through power saving from disabling macro cells. Network throughput increases even though there are 12 fewer cell sites active, and there is no loss in cell edge user throughput. Increasing the coefficient shows little or no gain in cell edge user throughput, whilst there is a loss in ECR, especially with coefficients 0.75 and 1.0. Coefficients 0 or 0.25 offer clearly the best configuration here. Fig. 4 illustrates the performance metrics of Configuration 4 scenario with $\alpha = 0.25$. Comparing the two configurations we can observe that the ECR is significantly larger in Configuration 1 as compared to Configuration 4. This is because in the latter pico cells supports a higher throughput and transmit more bits per power unit.

V. Conclusions

In this study we proposed an algorithm that optimizes energy efficiency by powering on and off the cells in HetNet environment. The algorithm that is based on simulated annealing has been compared to a baseline scenario where all cells are powered on. Simulation results show that significant energy reduction gains can be achieved by switching off cells while preserving or in some scenarios even improving cell edge user throughput due to interference reduction. Overall better energy efficiency can be achieved in configurations where pico cells are serving clusters of users.

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