Energy efficient heterogeneous network deployment with Cell DTX

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***Abstract*—This paper evaluates different means of reducing power consumption of macro base stations (BS) and heterogeneous mobile network deployments (HetNet) considering the time dimension. These approaches are based on the same idea of reducing the load of heavily loaded macro cells and putting them to discontinuous transmission (DTX) mode during the time of inactivity by either (1) macro cell densification or (2) offloading traffic to small cells. Activity factor of a BS is defined as the fraction of time the BS is transmitting over a fixed time period. It is shown that by macro cell layer network densification, the average daily area power consumption can be reduced by up to 73 % with the use of cell DTX. However, reducing the activity factor by macro layer densification is not cost effective, as already demonstrated in previous studies. Alternatively, by adding small cells and enabling their DTX capability, power consumption can be reduced by up to 29 %. Adding small cells is especially effective in terms of energy savings, when users are distributed around hot spots, where additional coverage and capacity is required.**

I. Introduction

Reduction of energy consumption in cellular network has become one of the priorities in telecommunication networks, driven by the following forces: (1) the need to reduce the increasing electricity bill of operators and (2) the society requirement to reduce the carbon footprint that causes the green gas emissions and global warming. The problem of energy consumption concerns not only the new cellular technologies and radio access networks, but also the legacy networks.

Base stations consume the largest part (80 %) of the total power consumption in wireless access networks, significant amount of which comes from the times when there are no active users transmitting. In fact, the constant power consumed by the base station when it is not transmitting is of the same order of magnitude as the variable power consumption part that depends on the data transfer [1]. However, the mobile networks today are designed for the peak traffic demand and kept active regardless of the low utilization during different times of the day. Hence, it has been shown that even during a very busy traffic hour of the day only few cells experience high load [1]. Therefore, most of the time a cell can be put into a sleep mode, thus reducing the constant (baseline) power consumption part from P_0 to a lower value δP_0, where $0 < \delta < 1$, thus achieving potentially significant energy savings. Note that $\delta = 1$ when the BS does not have the DTX capability. In this case the cell load only impacts the transmission-related power consumption.

DTX has been used for a long time in mobile terminals to achieve long battery life. The idea is to transmit only when there is a need or, otherwise, put the transmitter in a low power state. At the network side this technique is referred to as cell DTX, which is based on the hardware component deactivation feature that facilitates low power states. It enables node-level power consumption adaptation in accordance with traffic variation in a very short time scale (millisecond level).

In addition to sleep mode of operation, network deployment has also big impact on energy efficiency. Adding more capacity and enhancing bitrates can also increase the network energy efficiency in terms of bit per joule. However, this added capacity is just a potential and considering that this capacity is not utilized fully, this measure does not give an idea about how much power is consumed by a specific network deployment in an area. On the other hand, if one measures area power consumption, the densified solution will always look high power consuming due to the static power consumption. Therefore, in this study we use the area power ($\mathrm{W/km^2}$) together with the time dimension that considers the achieved bit rates for a given traffic demand in a random observation period (referred to as the BS activity factor), as the metrics for measuring energy efficiency of the particular network deployment.

Densification and capacity requirements can reduce network power consumption since the duration of transmit operations, i.e., activity factor, decreases as the capacity increases, enabling longer idle times during which a BS can be put to sleep. Macro BS densification is one potential way of adding more capacity and decreasing energy consumption of the network. Alternatively, adding small cells in dense areas with poor radio conditions in the macro cell layer can provide both the coverage and more capacity, thus offloading the macro BS and saving energy. If we can serve a user from a nearby small node instead of a faraway macro node then the extra energy used in the small node is often far less than the energy saved in the macro node. The more energy saving features we have in the network, the more effective this macro-offloading potentially becomes.

This paper investigates the means for operators to improve energy efficiency of their mobile networks by answering the following research questions: (1) How much energy can be saved using cell DTX and macro-offloading with small cells for a given traffic pattern?, (2) Can we empirically derive a relationship between energy savings, cell range, and DTX value in order to maximize the energy savings based on these two parameters?, and (3) What is the optimal network deployment with respect to energy efficiency that needs to satisfy the given traffic demand?

The remainder of the paper is organized as follows. Section 2 describes the related work. Section 3 presents the system model for studying the activity factor of the mobile access network deployment and deriving the portion of time in which a BS can be put to sleep to save energy. Section 4 defines the problem, followed by the power model and energy efficiency metrics in Section 5. Section 6 describes traffic generation that was used in simulations, which results are elaborated in Section 7. Finally, we conclude the paper, outlining plans for future work.

II. Related work

The energy saving potential of cell DTX has not been fully examined in the literature. In [1] the authors investigated the potential energy cost reduction of LTE network with different DTX schemes as a function of traffic in a metropolitan area. They showed that 61 % energy can be saved by putting the base stations' transceiver into sleep when not transmitting, by examining the traffic on the millisecond level and performing this evaluation for the specific cell size. S. Tombaz et al. examined the optimal macro base station deployment under the certain coverage and daily traffic variations requirements that can minimize the area power consumption [2], showing that the cell DTX feature favors network densification with lightly loaded cells, which if introduced already in the planning phase, can bring considerable energy savings (42 % more than only by putting base station to sleep when there is no data traffic). However, this densification may not be economically viable if done in the macro layer [3]. We have extended the paper [2] with small cell offloading and developing a generalized mathematical model to calculate the activity factor considering the time dimension for both small cell and macro cell layers, while using macro and small cell DTX.

Other related works looked into the means of increasing mobile network's energy efficiency by offloading the macro cell layer with small cells. A greedy BS deployment algorithm for offloading a macro base station with the set of micro base stations has been proposed in [4] in order to maximize the energy efficiency of the mobile network, while satisfying the capacity requirements. However, in their HetNet deployment the cell DTX was not used to reduce power consumption. K. Hiltunen studied in [5] the daily energy consumption of different LTE network densification alternatives, showing that energy efficiency can be considerably improved by densification of macro cells, or in HetNet scenarios using small cells to offload the most heavily users, with the help of cell DTX, or by switching off the unnecessary capacity cells during low-traffic hours. The difference from our work is that Hiltunen investigated the effect of cell DTX on the existing network deployment, while we also varied the number of cells and the cell size in order to find the optimum network deployment for macro and HetNet scenario from the energy perspective. In 3GPP LTE release 12 [6] they performed performance analysis of HetNet deployments with small cell on/off techniques. However, they used static cell load instead of base station activity in time dimension, computing the reduction in active subframe ratio using the time scale of hundreds of milliseconds for on/off transitions instead of energy savings. Furthermore, they did not use any configurable parameters in the power model, such as depth of sleep.

III. System model

Consider a wireless network in which mobile users are served with macro and femto BSs, denoted by B_m and B_f, respectively. The mobile users are associated with the BS that provides the strongest signal. Suppose that we know the association of each user i to BS $b_k \in \{B_m \cup B_f\}$ during one hour of observation period T, where $1 \leq i \leq N$, $1 \leq k \leq M$, N represents the number of mobile users, and M denotes the number of deployed BSs in the network. Each user wants to download a file of Ω bits during T. The users are served one at a time, i.e., the available bandwidth is allocated to one user at a time. The *activity factor* of the cell k, η_k, defined as the fraction of the time T that b_k is transmitting, can be calculated as the sum of the times that each associated user is served by this BS divided by T:

$$\eta_k = \frac{\sum_{i=1}^{N} t_{ki}}{T} = \frac{\sum_{i=1}^{N} (\Omega / r_{ki})}{T} = \frac{\Omega}{T} \sum_{i=1}^{N} \frac{1}{r_{ki}} = r_0 \sum_{i=1}^{N} \frac{1}{r_{ki}} \tag{1}$$

where r_{ki} is the current bitrate that the BS b_k allocates to the user i and r_0 is the average bitrate in the observation period. r_{ki} can be approximated by the Shannon formula:

$$r_{ki} = W \log_2(1 + \Gamma_{ki}) \tag{2}$$

where W is the bandwidth of one BS and Γ_{ki} represents the Signal to Interference Noise Ratio (SINR) for the user i in cell k. By substituting r_{ki} in (1) with (2) we obtain:

$$\eta_k = r_0 \sum_{i=1}^{N} \frac{1}{W \log_2(1 + \Gamma_{ki})} = \frac{r_0}{W} \sum_{i=1}^{N} \frac{1}{\log_2(1 + \Gamma_{ki})} \tag{3}$$

Note that the SINR equation is given by:

$$\frac{1}{\Gamma_{ki}} = \frac{1}{\mathrm{SINR}_{ki}} = \frac{1}{\mathrm{SIR}_{ki}} + \frac{1}{\mathrm{SNR}_{ki}} \tag{4}$$

where the Signal to Interference ratio (SIR) for the user i in cell k is defined as the received power from b_k to user i divided by sum of the received power of each interfering cell b_j:

$$\mathrm{SIR}_{ki} = \frac{P_{ki_k}}{\sum_{j \neq k} P_{ji_k}} \tag{5}$$

and the Signal to Noise Ratio (SNR) for the user i in the cell k is defined as the received signal power from b_k to user i divided by the noise power:

$$\mathrm{SNR}_{ki} = \frac{P_{ki_k}}{N} \tag{6}$$

Assuming a simplified path loss model of the channel given by the ratio of received and transmitted power:

$$L(r) = c_1 r^{c_2} \tag{7}$$

where r is the distance between transmitter and receiver in meters, c_1 is a constant that depends on antenna characteristics and the average channel attenuation, and c_2 is the path loss exponent, P_{ji_k} can be written as:

$$P_{ji_k} = \frac{P_t}{L(r_{ji_k})} = \frac{P_{\min} c_1 R^{c_2}}{c_1 r_{ji_k}^{c_2}} = P_{\min} (\frac{r_{ji_k}}{R})^{-c_2} = P_{\min} d_{ji_k}^{-c_2} \tag{8}$$

where r_{ji_k} and d_{ji_k} are the distance and normalized distance from base station *j* to the user *i* that resides in the cell *k*.

From here SIR_{ki} can be expressed as:

$$\text{SIR}_{ki} = \frac{d_{ki_k}^{-c_2}}{\sum_{j\neq k} d_{ji_k}^{-c_2}} \tag{9}$$

and SNR_{ki} as follows:

$$\begin{aligned}\text{SNR}_{ki} &= \frac{P_t/L_(r_{ki_k})}{N} = \frac{(P_{\text{min}}c_1R^{c_2})/(c_1r_{ki_k}^{c_2})}{N} \\ &= \frac{P_{\text{min}}}{N}(\frac{r_{ki_k}}{R})^{-c_2} = \frac{P_{\text{min}}}{N}d_{ki_k}^{-c_2} = \gamma_0 d_{ki_k}^{-c_2}\end{aligned} \tag{10}$$

where P_t is the transmit power, P_{min} is the minimum received power by users in the cell *k*, *R* is the cell radius, and γ_0 is SNR of the user *i* at the cell border.

Inserting (9) and (10) back into (4) results in:

$$\begin{aligned}\Gamma_{ki} &= \frac{1}{\frac{1}{\text{SIR}_{ki}}+\frac{1}{\text{SNR}_{ki}}} = \frac{1}{d_{ki_k}^{c_2}\sum_{j\neq k} d_{ji_k}^{-c_2} + \frac{N}{P_{\text{min}}}d_{ki_k}^{c_2}} \\ &= \frac{d_{ki_k}^{-c_2}}{\sum_{j\neq k} d_{ji_k}^{-c_2} + \frac{1}{\gamma_0}}\end{aligned} \tag{11}$$

By introducing the average activity factor of the BS η into (11), the SNR equation gets modified as follows:

$$\Gamma_{ki} = \frac{d_{ki_k}^{-c_2}}{\sum_{j\neq k}\eta_j d_{ji_k}^{-c_2} + \frac{1}{\gamma_0}} = \frac{d_{ki_k}^{-c_2}}{\boldsymbol{\eta}_k\cdot \boldsymbol{d}_{ki_k}^{-c_2} + \frac{1}{\gamma_0}} \tag{12}$$

where in the last expression the scalar product involves all components but the current cell *k*, i.e. $\boldsymbol{\eta}_k = (\eta_j)_{j\neq k}$ and $\boldsymbol{d}_{ki_k} = (d_{ji_k})_{j\neq k}$. The constant $c_2 \approx 3.52$ is the path loss exponent (COST231 urban model) and γ_0 is the SNR at cell border. The important property of this expression is that it cancels out the constant transmit power, which is a function of cell radius, thus removing the dependence of SNR on cell size. Furthermore, it shows that Γ_{ki} is a function of η_k, and since we already showed in (3) that η_k is a function of Γ_{ki}, it follows that:

$$\boldsymbol{\eta} = f(\boldsymbol{\eta}) \tag{13}$$

This activity factor equation can be written as a recurrence equation, which can be solved by iteratively finding the fixed point $\boldsymbol{\eta} = (\eta_k)_{k=1}^M = (\eta_1, ..., \eta_M)$ for the deployed network.

Traffic demand factor is defined as the ratio between offered traffic load and maximum cell throughput:

$$\vartheta = \frac{n_{\text{active}} r_0}{W\nu_{\text{max}}} = \frac{\bar{\alpha}\rho A(R) r_0}{W\nu_{\text{max}}} \tag{14}$$

where n_{active} denotes the number of active users, ν_{max} is the maximum sustainable link spectral efficiency in practice achieved by the highest modulation and coding scheme, ρ represents the user density, and $\bar{\alpha}$ refers to the average daily traffic variation in terms of the percentage of the number of active users.

We propose an empirical model where the cell activity factor is defined as a function of the traffic demand factor. Figure 1 illustrates this function, using the uniform user distribution with 1000 users/km^2 for different cell sizes, which is equivalent to the fixed cell size and varying user density. In this figure, the feasible load of the centre cell was considered and the mentioned path loss model.

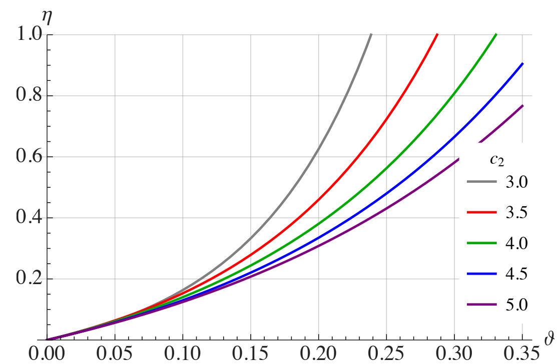

Fig. 1. Cell activity factor vs. traffic demand factor function

As illustrated in Figure 1, assuming that a cell can handle 60 % activity or in other words time load, the traffic demand factor needs to be lower than 23 % due to the interference. A simple empirical model has been derived to compute the activity factor, which can tell us how much time the BS can be put to sleep based on the cell activity and traffic demand factor:

$$\eta \approx 0.25(e^{4.3\vartheta(1+\vartheta)} - 1), c_2 \approx 3.52 \tag{15}$$

IV. Problem Statement

Given that we know the associations of users to BSs, the locations of users, the locations of BSs, and the demand of each user during the observation period *T*, our objective is to find what are the achievable bitrates of these users during *T* and what is the sleep time σ_k of each associated BS b_k.

A base station can be put to DTX mode during the idle time, i.e., when there are no data transmissions. Therefore, by computing and summing up all the output bitrates during *T*, and subtracting them from 1, we can compute the fraction of the time that the base station can be put to sleep:

$$\begin{aligned}\sigma_k &= 1-\eta_k = 1-\frac{\sum_{i=1}^{N}(\Omega/r_{ki})}{T} = 1-\frac{\Omega}{T}\sum_{i=1}^{N}\frac{1}{r_{ki}} \\ &= 1-r_0\sum_{i=1}^{N}\frac{1}{r_{ki}}\end{aligned} \tag{16}$$

By decreasing the activity factor of the cell, the sleep time can be increased. The power consumption model introduced in [2] demonstrates that the power consumption of the base station can be reduced by decreasing the activity factor, i.e., network densification:

$$E_k = \zeta P_k\eta_k + (1-\delta)P_0\eta_k + \delta P_0 \tag{17}$$

where P_k denotes the power spectral density per BS in cell k and ζ represents the portion of the power consumption due to feeder losses and power amplifier.

This brings us to our main objective, which is to reduce the activity factor of macro base stations and minimize the daily power consumption in the given area. We will investigate two different ways to achieve this: (1) by optimizing a cell range of macro base stations and putting them to sleep and (2) by adding the optimum number of femto cells to offload the macro base stations and putting the small cells to sleep.

Additionally, as the activity factor depends on the number of active users in the network at a given time, we will look into different types of distributions of the active users: the homogeneous and inhomogeneous distribution with different user density values, in order to examine the potential energy savings that can be obtained in different environments by network deployment with cell DTX.

V. Power consumption

In order to find the most energy efficient mobile network deployment that can minimize the daily power consumption, while satisfying the users' traffic demand in the particular area, it is important to use a proper metrics to quantify power/energy consumption of different network topologies and load distributions in order to derive correct conclusions. However, when comparing two network topologies, the result of energy efficiency (EE) metrics will greatly depend on the network conditions in which the power consumption measurement is made, i.e., if these networks transport different data volumes. Therefore, it is essential that the networks are compared when transporting the same number of data bits.

The EE metrics should capture the power/energy consumed by a network to transport Ω bits in an observation period T. The network consists of the number of base stations N_{BS} with the intersite distance $R\sqrt{3}$, covering an area A_{net}. Ω is evenly distributed over users in A_{net}.

This paper adopts the energy metrics consisting of the *area power consumption*, P, that is the total power consumption of the network in the coverage area A_{net}, expressed in W/km^2:

$$P = \frac{P_{\text{net}}}{A_{\text{net}}} \tag{18}$$

where P_{net} is the total power consumed by the network in [W]. The optimal energy efficiency is achieved when P is minimized, thus reducing the power consumption in the network area.

The power consumption model introduced in [2] computes a *daily average area power consumption* of the network consisting M number of BSs with cell DTX as:

$$E_t[P^t_{\text{area}}(R)] = \frac{1}{|t|}\sum_{t=1}^{24}\frac{\sum_{k=1}^{M} E_k}{A(R)} \tag{19}$$

which is also used in this paper.

In macro base station deployment with cell DTX, the power consumption model of a base station, E_k, is given by equation (17), while in the heterogeneous deployment of macro base stations and femto cells, E_k has been modified to also include the power consumption of femto cells:

$$\begin{aligned} E_k &= (\zeta P_k + (1-\delta)P_0)\eta_k + \delta P_0 \\ &\quad + [n(\zeta P_k + (1-\delta)P_0)\eta_k + \delta P_0]_{\text{femto}} \end{aligned} \tag{20}$$

VI. Traffic generation

In a homogeneous distribution, users are randomly distributed in a km^2 area according to Poisson's distribution, with densities of 500, 1000, to 2000 users/km^2 representing the dense urban, urban, and suburban areas according to EARTH methodology [7]. To account for traffic fluctuations during the day, referred to as $\alpha(t)$, we consider the traffic input from the daily profile showing 22 o'clock, the highest activity time according to [7].

An inhomogeneous network is simulated using the correlated lognormal user distribution over the 19 macro cells area with 1 km radius and $\sigma = 4$ dB. This user distribution has been generated from the correlated data matrix using an exponential kernel with 250 m correlation distance. The PDF function of this distribution is shown in Figure 2, illustrating several hot spot areas that are more populated with users than the rest of the service area.

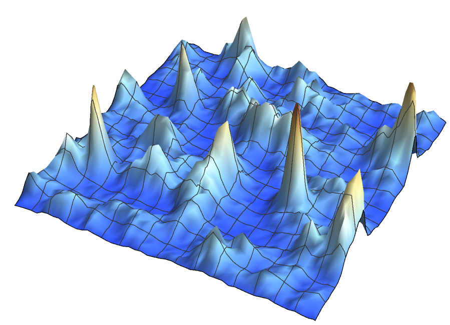

Fig. 2. PDF function for inhomogeneous user distribution over 19 cell area

VII. Simulation results

This section illustrates the daily average area power consumption of different BS densification strategies utilizing cell DTX for both 1) macro only and 2) HetNet scenarios. The simulations are implemented and executed in the WiPack[1] system demonstrator, which is developed in Mathematica [8].

We consider a hexagonal network deployment consisting of 19 macro BSs with omnidirectional antennas with 15 dBi antenna gain. The BSs are put in the center of the cells with varying cell radius from 100 m to 1000 m in the urban scenario. The system operates at 2 GHz with 10 MHz bandwidth. In the inhomogeneous user distribution scenario small cells are deployed around hot spots of dense areas. In order to emulate the time dimension and be able to calculate the sleep time under realistic assumptions, considering the inter-cell interference, we used the iterative time static simulations described in Section III [9]. The time static simulation model has constant number of users distributed over an area, each having a fixed file size, $\Omega = 18$ MB, to transmit in the observation period of one hour. The simulation results have been generated with COST231 path loss model for an urban area and with varying macro cell DTX values. We adopt the power model parameters from the EARTH

[1] Göran Andersson is an author of this Mathematica package. For those interested in trying it out, please send an email to goeran@kth.se.

project deliverable [7]: (1) for macro cells: $\zeta = 4.7$, $P_0 = 130\,\mathrm{W}$, $P_k = 20\,\mathrm{W}$ and (2) small cells: $\zeta = 8$, $P_0 = 4.8\,\mathrm{W}$, $P_k = 0.05\,\mathrm{W}$, while $\nu_{\max} = 6$ bps/Hz. The QoS constraints, defining the minimum transmit power that satisfies the coverage requirement and the minimum achieved bitrate of the users in the cells, are: $P_{\min} = -70\,\mathrm{dBm}$ and $r_{\min} = 8$ Mbps, respectively.

We start by analyzing the simulation results of the macro only deployment. Figure 3 shows the average daily area power consumption as a function of cell range for different levels of sleep, i.e. DTX value δ. The obtained graph shown in Figure 3 confirms the findings presented in [2].

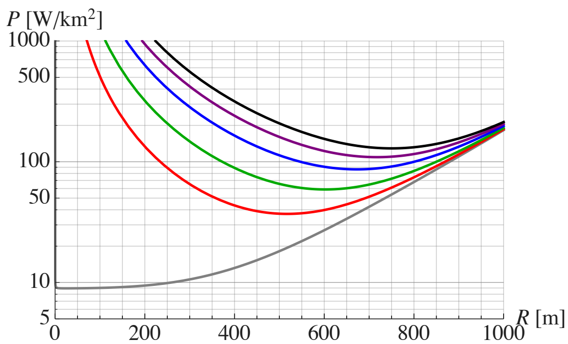

Fig. 3. Average daily power consumption as a function of the cell radius

It can be observed that for a given DTX value, δ, one can find the optimum cell range, $R_{\min}$, that yields the minimum power consumption, $P_{\min}$. The $R_{\min}$ value decreases with network densification, reducing the macro cell load and increasing the portion of time that macro BSs spend in DTX mode, thus decreasing the average daily power consumption. Continuing to increase the cell radius more than $R_{\min}$ leads to a further increase of average daily power consumption, due to an increase of aggregated power consumed by BSs in idle state.

Plotting $R_{\min}$ and $P_{\min}$ against δ in a log-log diagram gives, in both cases, a straight line fit. This implies a simple power function model shown in Figure 4:

$$R_{\min} \approx 750\,\mathrm{m} \times \delta^{0.16}, P_{\min} \approx 125\,\mathrm{W/km^2} \times \delta^{0.56} \tag{21}$$

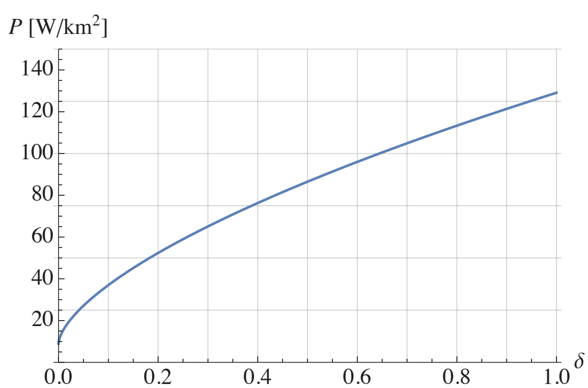

Fig. 4. Minimum power consumption under optimum cell range for a given DTX factor

It can be observed from Figure 4 that for $\delta = 0.5$ the area power consumption has been reduced for $1 - 0.5^{0.56} \approx 1/3$, by decreasing the cell radius from 750 m to 650 m. The maximum power reduction of 73 % can be obtained with $\delta = 0.1$ and optimum cell size (i.e., $R_{\min}$ of 525 m), when compared to the deployment with $\delta = 1$ and $R_{\min}$ of 750 m.

The effect of reduced power consumption can also be observed in Figure 3 when applying cell DTX to the macro cell deployment with $R_{\min}$ of 750 m. Figure 3 shows that 53 % energy can be saved with $\delta = 0.1$ without changing the cell size.

In the second simulation, we examined variously loaded macro cells with 500m inter-site distance that are being offloaded with femto cells with 50m inter-site distance. Figure 5 illustrates how activity factor of macro cells, obtained at different user densities, decreases with the number of added femto cells per macro cells. Note that the activity factor for this HetNet scenario is computed with a procedure similar to the homogeneous case (12), but the gains of the small cells ($d_{ki_k}^{-c_2}$) are multiplied with a -25 dB factor to reflect the lower transmit power in small cells.

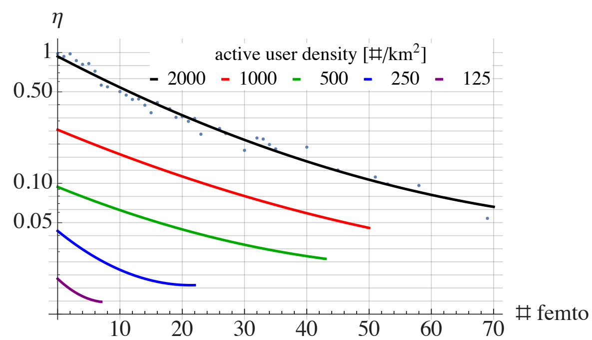

Fig. 5. Activity factor of macro layer vs. number of added femto cells per macro cell for different user densities

Next, we investigated what happens with the power consumption when offloading heavy loaded macro cells with femto cells. Figure 6 shows the results of this simulation, with only macro cells having cell DTX enabled.

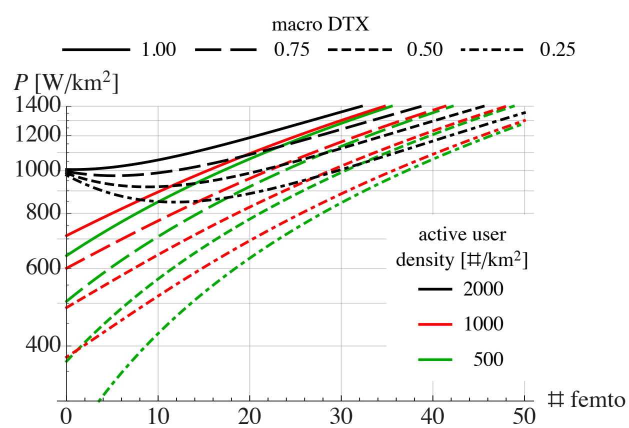

Fig. 6. Power consumption at varying user densities vs. number of femto cells (without cell DTX) per macro cell

Observe in the black curves a power decrease at very high user density of 2000 users/km^2, in which case the activity factor of the macro cell is close to 1, i.e., there is no time for sleep using cell DTX. In all other curves with lower user densities, the power consumption increases with added femto cells. This indicates that offloading macro cells with femto cells is, from the power perspective, effective only when macro cells are heavily loaded. The power can be further decreased by enabling macro DTX, which in case of 12 added femto cells and $\delta = 0.25$ reaches 9 % compared to the macro only deployment with cell size of 500 m and without macro DTX (i.e., indicated in Figure 6 with zero femto cells and $\delta = 1$). The convergence of the black curves towards a single point at $n = 0$ comes from the fact that the power formula doesn't gain from cell DTX when the load is 100 %.

Figure 7 presents the power consumption results for the same HetNet scenario, however with enabled cell DTX on both macro **and** femto cells. The femto DTX is set to 0.5, while macro DTX values are the same as in previous figure. The results show that power consumption reduction up to 29 % can be achieved when enabling DTX feature on both the 23 added femto cells and the macro cells (i.e., using 0.25 macro DTX and 0.5 femto DTX), compared to the macro only deployment with cell size of 500 m and without macro or femto DTX. It can be concluded that the use of femto DTX decreases P_{min} of HetNet deployment, however at the cost of deploying more femto cells.

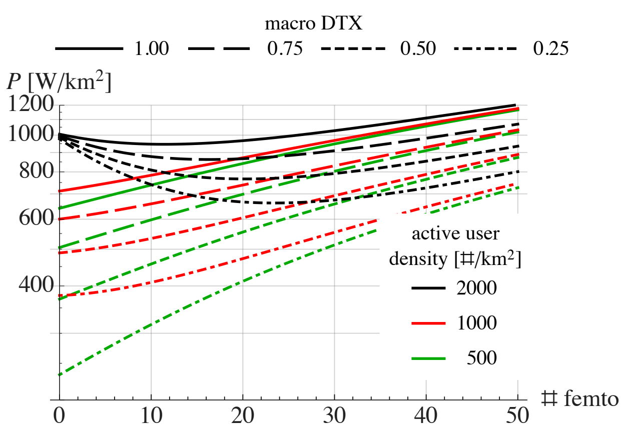

Fig. 7. Power consumption at varying user densities vs. number of femto cells (with 0.5 DTX) per macro cell

Similar simulations were performed with inhomogeneous user distribution in order to evaluate if offloading macro cells with femto cells can give better performance. The results illustrated in Figure 8 show that in high density population (of 2000 users/km^2) energy savings of up to 19 % can be obtained with 7 added femto cells and 0.25 macro DTX, which is higher than in the same deployment with homogeneous user distribution. Note that this savings represent the worst case scenario, since they were obtained without femto DTX. By also including femto DTX the savings are expected to be much higher. This is planned to be verified as part of future work.

VIII. Conclusion

This paper demonstrates the daily average area power consumption savings by implementing different energy efficiency features based on the cellular network deployment. In macro base station and small cell scenarios it has been shown that power consumption decreases only when offloading a heavily loaded macro cell with small cells or by increasing the size of

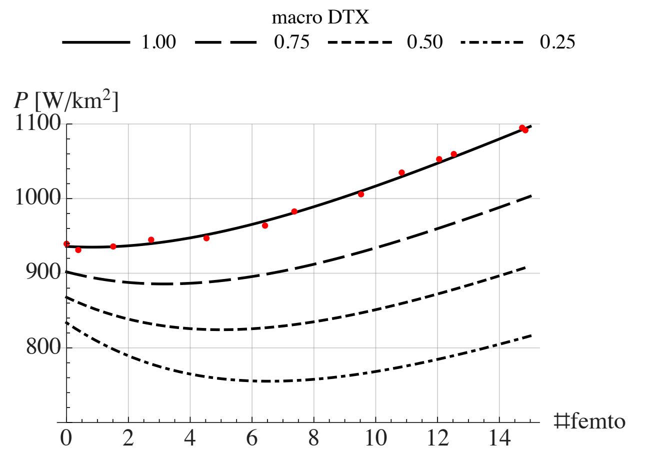

Fig. 8. Power consumption in inhomogeneous high density population vs. number of femto cells per macro cell with varying macro cell DTX

macro cells. The best option for operators to achieve the power savings is densifying macro cell layer. We show in this paper that up to 73% can be obtained by network densification and using cell DTX on top of this. However, since the cost is also very important for operators, it is not realistic to have such a dense macro cell layer. When DTX is enabled in femto cells, increasing power savings (of up to 29 %) can be achieved by adding small cells. Additionally, it has been shown that when heavily loaded users are distributed in hot spots, deploying small cells in these spots to offload the traffic can result in further power savings.

Future work consists of investigating massive MIMO beamforming with cell DTX as a way to improve the energy performance of mobile access networks.

Acknowledgment

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