Energy Efficient Network Deployment with Cell DTX

Sibel Tombaz, Sang-wook Han, Ki Won Sung and Jens Zander

***Abstract*—Cell discontinuous transmission (DTX) is a new feature that enables sleep mode operations at base station (BS) side during the transmission time intervals (TTIs) when there is no traffic. In this letter, we analyze the maximum achievable energy saving of the cell DTX. We incorporate the cell DTX with a clean-slate network deployment, and obtain optimal BS density for lowest energy consumption satisfying a certain quality of service (QoS) requirement considering daily traffic variation. The numerical result indicates that the fast traffic adaptation capability of cell DTX favors dense network deployment with lightly loaded cells, which brings about considerable improvement in energy saving.**

***Index Terms*— Energy Efficiency, Cell DTX, Network Deployment, Cell Load, Traffic Profile.**

I. Introduction

MOBILE operators are facing an exponential traffic growth due to the proliferation of portable devices that require a high-capacity connectivity. This, in turn, leads to a tremendous increase in energy consumption of wireless access networks [1]. A multitude of studies have been recently proposed to increase the energy efficiency of these networks. Among them, cell DTX is a new hardware feature enabling the deactivation of some components of a BS during the empty TTIs. With the introduction of cell DTX, a cell can be put into sleep mode when there is no traffic which significantly lowers the idle power consumption. Unlike long term sleep schemes [1] that aim to switch off the cells completely during low traffic periods, cell DTX leaves certain parts of the cells active to ensure that the cells will be immediately activated upon request. This enables node-level power consumption adaptation in accordance with traffic variation in a very short time scale (millisecond level) without necessitating any network level cooperation schemes.

The energy saving potential of cell DTX has been discussed in the literature [2], [3]. However, no quantitative analysis is performed to evaluate the savings. Furthermore the fact that energy saving through cell DTX is closely related to the initial network deployment has been ignored. This arises from the fact that the network density determines the cell load levels in the network which, in return, impacts the deactivation time of each cell with cell DTX. Therefore, cell DTX should be incorporated at the planning stage in order to maximize the energy saving.

In this letter, we analyze the maximum achievable energy saving with cell DTX. To this end, we obtain the optimum BS density that minimizes the daily average area power consumption under certain coverage and QoS constraints assuming that cells have fast traffic adaptation capability due to cell DTX. We observe that a closed-form expression for the objective function is very difficult to obtain because of the coupling between cell load and network density which directly affects the daily energy consumption. Therefore, we propose a simple algorithm to solve the optimization problem considering the daily traffic variation and quantify the energy saving through optimized energy efficient network deployment with cell DTX.

S. Tombaz (corresponding author), S.-w. Han, K.W. Sung, and J. Zander are with Communication Systems Department, KTH Royal Institute of Technology, Stockholm, Sweden (e-mail:{sibel, swhan, sungkw, jenz}@kth.se. The work was supported by EIT ICT Labs.

II. System Model

We consider an OFDM network with M number of BSs covering a compact region $\mathcal{A}$ (km^2). Let user i be connected to BS b_i and the set $\beta_k = \{i : b_i = k\}$ contains the users connected to BS k. P_k is the power spectral density per resource block (RB), the minimum time-frequency scheduling unit, in cell k. Consider a time instant where the link gain between BS j and user i is stationary and given by g_{ij}.

In addition, we define the load or cell resource utilization as the fraction of time-frequency resources that are scheduled for data transmission in a given cell. The entire network load is given by a vector $\boldsymbol{\eta}$=$(\eta_1, \eta_2, ..., \eta_M)$, where $\eta_k \in [0, 1]$, $\forall\, k$. Then, average signal to interference plus noise ratio (SINR) of a user $i \in \beta_j$ that is served by BS j is defined as

$$\gamma_i(\boldsymbol{\eta}) = \frac{g_{ib_i} P_j}{\sum_{k\neq j}^{M} \eta_k \, g_{ik} P_k + \sigma^2}, \tag{1}$$

where σ^2 is the noise power. Note that here we consider load-dependent interference which plays an important role in accurate performance analysis. In this case η_k can be interpreted as the probability of receiving interference from cell k. Consequently, $\sum_{k\neq j}^{M} \eta_k \, g_{ik} P_k$ denotes the time-averaged interference power. The corresponding achievable data rate of user i per RB is modelled considering average SINR, i.e.,

$$r_i(\gamma_i(\boldsymbol{\eta})) = W_{RB} \min \left[\log_2(1 + \gamma_i(\boldsymbol{\eta})),\ \nu_{max} \right], \tag{2}$$

where W_{RB} is the bandwidth of one RB and ν_{max} reflects the maximum sustainable link spectral efficiency in practice by the highest modulation and coding scheme. Note that the corresponding achievable data rate will be $c_i(\boldsymbol{\eta}) = N_{RB} \times r_i(\gamma_i(\boldsymbol{\eta}))$, where N_{RB} is the maximum number of RBs at frequency domain.

Let $r_i(\gamma_i(\boldsymbol{\eta}))$ be the function describing the effective bit rate per resource unit. Therefore, when we assume the demand of user i as Ω_i, the required resource units to serve user i is $\frac{\Omega_i}{r_i(\gamma_i(\boldsymbol{\eta}))}$. Let T denote the total number of resource units in a considered observation period of frequency-time domain. We define ϕ_i^k as the proportion of resource consumption of cell k to serve user $i \in \beta_k$. By these definitions, we have the following formula,

$$T\phi_i^k = \frac{\Omega_i}{r_i(\gamma_i(\boldsymbol{\eta}))}. \tag{3}$$

Observing that $\eta_k = \sum_{i\in\beta_k} \phi_i^k$, we have the following equations:

$$\eta_k = \sum_{i\in\beta_k} \phi_i^k = \sum_{i\in\beta_k} \frac{\Omega_i}{Tr_i(\gamma_i(\boldsymbol{\eta}))}, \quad (4)$$

$$= \sum_{i\in\beta_k} \frac{\Omega_i}{Tr_i(\frac{g_{ik}P_k}{\sum_{j\neq k}^{M} \eta_j\, g_{ij}P_j+\sigma^2})}. \quad (5)$$

Note that η_k represents the resource utilization in time domain in this work because we assume that the available RBs are scheduled at the frequency domain first in order to maximize the available time for cell DTX.

A. The Feasible Load Concept

It is observed from (5) that the load of cell k is a function of the load levels of the other cells in the network. This is due to the fact that the load of interfering BSs has a direct impact on the SINR of the users for a cell k. This coupling relation creates the *"feasible load problem"* [4] in which the objective is to find a load vector $\boldsymbol{\eta}$ that balances the resource utilization with the interference-dependent resource demand in all cells which can be written mathematically as below [4]:

$$T\,\eta_k = \sum_{i\in\beta_k} \frac{\Omega_i}{r_i(\frac{g_{ik}P_k}{\sum_{j\neq k}^{M} \eta_j\, g_{ij}P_j+\sigma^2})}. \quad (6)$$

In order to define the feasible load levels of the cells for a given area traffic demand during an observation period t, we adopt the iterative time static simulation concept proposed in [4].

B. Area Power Consumption

In this work, area power consumption is used as an energy efficiency metric instead of bit/joule because it enables an intuitive understanding of the achieved energy saving. This metric relates the total power consumed in the network to the corresponding network area $\mathcal{A} = M \times 3\sqrt{3}R^2/2$, given by

$$\mathcal{P}_{area} = \frac{\sum_{k=1}^{M} E_k}{\mathcal{A}}, \quad [\text{W/km}^2] \quad (7)$$

where R and E_k denote the cell range and the power consumption of the BS k in the network, respectively. Here it is assumed that a cell can be either in *active* state, i.e., there is at least one user requesting a service, or in *idle* state, i.e., there is no active user. Traditional BSs consume considerable amount of power even when there is no user in the cell, defined as baseline power consumption, P_0 [5]. However, with a recent hardware improvement [2], a cell can be put into DTX mode during *idle* state which decreases the baseline power consumption to $P_s = \delta\, P_0$, where $0 \leq \delta < 1$. Based on these assumptions, average power consumption of cell k with the load $\eta_k \in \boldsymbol{\eta}$ can be written as below:

$$E_k = \zeta\, P_k\, \eta_k + (1-\delta)P_0\eta_k + \delta P_0. \quad (8)$$

Here, as we mentioned, P_k denotes the power spectral density per RB in cell k, whereas ζ represents the portion of the power consumption due to feeder losses and power amplifier. Thus, $(1-\delta)P_0\eta_k$ denotes the load dependent baseline power consumption arising from the fast traffic adaptation capability of cell DTX. Note that $\delta = 1$ represents the case where the BS does not have the DTX capability and therefore consumes $E_k = \zeta\, P_k\, \eta_k + P_0$.

III. Energy Efficient Network Deployment

Based on the system model presented in previous section, here, we introduce the optimization problem and propose a solution.

A. Problem Formulation

Our main objective is to minimize the daily average area power consumption under certain coverage and QoS constraints by optimizing cell range R considering $i)$ Case 1: cells' DTX capability is considered (δ $\in$[0,1)), $ii)$ Case 2: cells do not have DTX capability (δ=1). In this way we will analyze whether or not the incorporation of cell DTX at the planning phase changes the deployment for energy efficient wireless access networks.

First, we define the daily average area power consumption by

$$\mathbb{E}_t[\mathcal{P}_{area}^t(R)] = \frac{1}{24}\sum_{t=1}^{24} \mathcal{P}_{area}^t(R), \quad (9)$$

where, $\mathcal{P}_{area}^t(R)$ is the total average power consumed in the network to the corresponding network area at the discrete time index per an hour $t \in$ [1, 24].
So, we can define $\mathcal{P}_{area}^t(R)$ as follows:

$$\mathcal{P}_{area}^t(R) = \frac{\sum_{k=1}^{M} E_k^t(P_k, \eta_k^t)}{\mathcal{A}(R)} \quad \forall\, t \in [1, 24], \quad (10)$$

where

$$E_k^t(P_k, \eta_k^t) = \zeta\, P_k\, \eta_k^t + (1-\delta)P_0\eta_k^t + \delta P_0. \quad (11)$$

Intuitively, the value of $E_k^t(P_k, \eta_k^t)$ is approximately decided by the cell range R. However, it is difficult to formulate a closed form of $E_k^t(P_k, \eta_k^t)$ as a function of R due to the coupling relation between $\eta_k^t(\boldsymbol{\eta^t})$ and R. Therefore, we estimate the feasible cell load vector $\boldsymbol{\eta^t}$ satisfying (6) via iterative time static simulation for accurately evaluating the network performance and the energy consumption.

Since our main goal is to minimize the daily average area power consumption under certain coverage and QoS constraints by optimizing cell range R, we can now formulate this problem as:

$$\underset{R}{\textbf{Minimize}}\ \mathbb{E}_t[\mathcal{P}_{area}^t(R)] = \frac{1}{24}\sum_{t=1}^{24} \mathcal{P}_{area}^t(R), \quad (12a)$$

$$\textbf{subject to}\ F_{\chi\%}\big[\boldsymbol{c}(\boldsymbol{\eta}^{bh})\big] \geq r_{min}, \quad (12b)$$

$$g_{ik}P_k \geq P_{min}, \quad \forall\, k \quad (12c)$$

where $F_{\chi\%}[.]$ denotes the χ^{th} percentile of the cumulative distribution function (CDF) of the random variable in the blanket. Here, the first condition ensures that χ^{th} percentile user data rate at busy hour, i.e., $c^{\chi\%} = F_{\chi\%}\big[\boldsymbol{c}(\boldsymbol{\eta}^{bh})\big]$, is higher than r_{min} Mbps, and the second condition ensures full network coverage, which means that the received power of user i in a cell k is above a given threshold, P_{min}.

Below, the objective function is expressed in detail:

$$\mathbb{E}_t[\mathcal{P}^t_{area}(R)] = \frac{1}{24}\sum_{t=1}^{24} \frac{\sum_{k=1}^{M} \zeta\, P_k\, \eta^t_k + (1-\delta)P_0\eta^t_k + \delta P_0}{\mathcal{A}(R)}. \tag{13}$$

In order to present the dependence of the objective function on the cell size, we first provide the functional relationship between η^t_k and R in the following corollary.

Corollary 1 *The feasible load level of each cell η^t_k, $\forall\, k$, $\forall\, t \in [1, 24]$ is increasing with R^x, where $x > 2$.*

Proof of Corollary 1: Under the constant user density assumption, number of active users in a cell during a given hour t is increasing with R^2. On the other hand, user's data rate $r_i(\gamma_i(\boldsymbol{\eta}))$, $\forall\, i \in \beta_k$ is decreasing with R due to higher interference level. Therefore, the feasible load level of each cell $\eta^t_k = \sum_{i\in\beta_k} \phi^k_i = \sum_{i\in\beta_k} \frac{\Omega_i}{T r_i(\gamma_i(\boldsymbol{\eta}^t))}$ will increase with R^x, $x > 2$. $\square$

Regarding P_k, we choose its value as the minimum transmit power required to ensure full coverage, i.e., $P_k : g_{ik}P_k = P_{min}$. This also represents the optimum transmit power for interference limited systems considering that energy consumption is strictly increasing with P_k. Based on the general form of the path loss model, i.e., $g^{dB}_{ik} = 10\,log_{10}(c_1) + 10\,c_2\,log_{10}(d_{ik})$, the functional relationship between transmit power and cell range will be $P_k(R) = \frac{P_{min}}{c_1} R^{c_2}$. Here c_1 and c_2 denote the model parameters.

Based on the given relationships, daily average area power consumption will have the following dependence on cell range:

$$\mathbb{E}_t[\mathcal{P}^t_{area}(R)] \approx f_1(R^{x+c_2-2}) + f_2(R^{x-2}) + f_3(R^{-2}).$$

Here $f_1(.)$, $f_2(.)$ and $f_3(.)$ denote the relationship between each term of $\mathbb{E}_t[\mathcal{P}^t_{area}(R)]$ with R. It is clearly observed that $\mathbb{E}_t[\mathcal{P}^t_{area}(R)]$ is a unimodal function since, while $f_1(R^{x+c_2-2}) + f_2(R^{x-2})$ is monotonically increasing with R, $f_3(R^{-2})$ is monotonically decreasing. Therefore, there always exists a non-null and finite cell range that minimizes $\mathbb{E}_t[\mathcal{P}^t_{area}(R)]$, $\forall\, \delta \in [0, 1]$.

B. Proposed Solution

We propose a simple algorithm to solve the optimization problem in (12), $\forall\delta \in$ [0,1]. For each cell range $R \in \boldsymbol{R}$, Algorithm 1 first defines the minimum transmit power that satisfies the coverage requirement. Then, for each hour t, the feasible load vector $\boldsymbol{\eta}^t$ at time t is determined by using an iterative approach that solves (6). This time-static iterative simulation uses the number of active users in the network at a given time t, i.e., $N^t_{act}(R) = \rho \times \alpha(t) \times \mathcal{A}(R)$ as an input together with initial load vector and accuracy parameter. Here ρ and $\alpha(t)$ denote the user density and daily traffic variation, respectively. Vector $\boldsymbol{\eta}^t$ is then used to calculate the average area power consumption and CDF of the user data rates during that hour t. We finally determine the daily average area power consumption $\mathbb{E}_t[\mathcal{P}^t_{area}(R)]$ and χ percentile user data rate at busy hour $c^{\chi\%}$ for a given $R \in \boldsymbol{R}$.

The search over cell ranges aims at finding the optimum cell range R^* that fulfills (12). This overall search algorithm increasing R by a step size $\triangle$ will be stopped if the objective value are increasing $\mathbb{E}_t[\mathcal{P}^t_{area}(R)] > \mathbb{E}_t[\mathcal{P}^t_{area}(R-\triangle)]$ or χ percentile user data rate at busy hour is less than r_{min} Mbps. This is due to the fact that while $\mathbb{E}_t[\mathcal{P}^t_{area}(R)]$ has a convex relation with R, $c^{\chi\%}$ is a non-increasing function of R. Therefore, the QoS constraint given in (12b) determines the maximum cell range that can be selected for the deployment.

Algorithm 1 Calculate the cell range R^* that optimizes (12)

```
for all R = R_min to R_max do
    Compute P_k(R) = (P_min / c_1) R^{c_2} for all k
    for all t ∈ [1, 24] do
        Calculate active user at time t, N^t_act(R)
        Using N^t_act, find η^t_k(R) for all k from (6)
        Compute r_i(γ_i(η^t(R))) for all i
    end for
    Compute E_t[P^t_area(R)]
    if E_t[P^t_area(R)] < E_t[P^t_area(R − △)]
    and F_χ%[c(η^bh)] ≥ r_min then
        Update R = R + △
    else
        Return R* = R, Stop.
    end if
end for
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IV. Simulation Results

In this section, we numerically illustrate how the incorporation of cell DTX at the planning phase increases the achievable energy saving by comparing the deployment for the lowest daily energy consumption R^* for i) Case 1: $\forall\delta \in$ [0,1) (Cell DTX is incorporated with clean-slate network deployment) ; ii) Case 2: $\delta = 1$ (Cells do not have DTX capability).

We consider a network with a regular hexagonal layout consisting of 19 sites equipped with one omni-directional antenna with 15 dBi antenna gain and exhibit cell range varies between 100 and 800 meters. The simulated system operates at 2 GHz with 10 MHz bandwidth. We utilize the Okumura-Hata path loss model for an urban area based on 3GPP specifications [6] with 8 dB user noise figure. Users are randomly distributed over the area with a density of ρ=1000 (users/km^2). To account for the traffic fluctuations during a day $\alpha(t)$, we consider an approximated daily pattern based on the downlink traffic measurements presented in [5] by assuming that user behavior is unchanged. Here we consider that each user demands Ω=18 MB within a duration of one hour which corresponds to the peak area traffic demand of 40 Mbps/km^2, a reasonable estimate for 2015 [5]. For the proposed algorithm, we set ζ=4.7, P_0=130 W based on [5], and ν_{max} = 6 bps/Hz. Moreover, the QoS constraints are defined as P_{min}=-70 dBm, r_{min}=8 Mbps [5].

Fig. 1 depicts the daily average area power consumption as a function of cell range for both cases, assuming $\delta = 0.1$ for Case 1. Note that the maximum cell range that fulfills (12b) for r_{min}=8 Mbps is defined as $\hat{R}$=720 meters regardless of δ. We observe in Fig. 1 that when cell DTX is incorporated at the planning stage, higher densification tends to be preferred which also brings significant energy savings. This is mainly because Case 1 takes into consideration that lower cell load levels which create long deactivation periods originating from densification can be efficiently exploited by cell DTX.

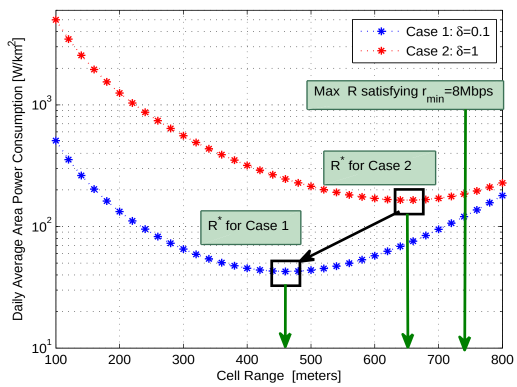

Fig. 1: Daily average area power consumption as a function of cell range for $\delta = 0.1$, r_{min}=8 Mbps .

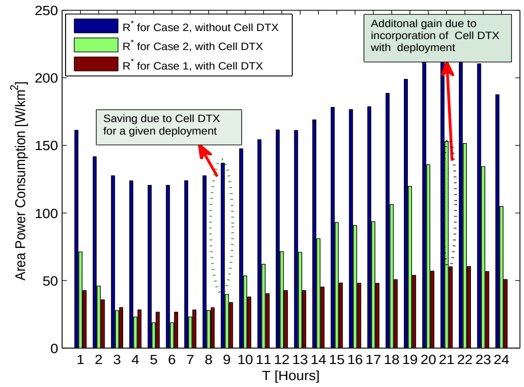

Fig. 3: Daily area power consumption variation for $\delta = 0.1$.

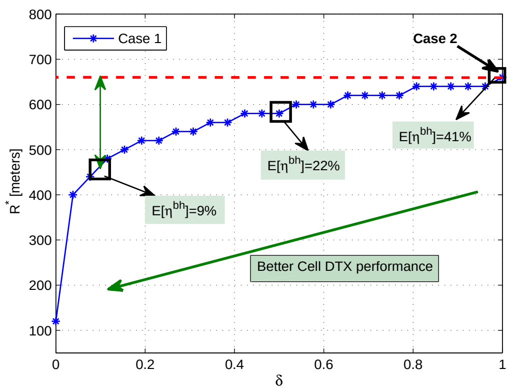

Fig. 2: Impact of Cell DTX performance on optimum cell ranges and busy hour cell load levels for r_{min}=8 Mbps.

Normally, operators would design their networks for minimum network deployment cost, i.e. with as few BS as possible. Assuming, however, instead that our main interest is to obtain the most energy efficient network deployment regardless of cost, we may find the BS density that gives us the lowest daily energy consumption in the considered cases. In this respect Fig. 2 shows the optimum cell ranges and the related average feasible load levels at busy hour $(E[\boldsymbol{\eta}^{bh}(R^*)])$ as function of cell DTX performance represented by δ. We can see that employing cell DTX at the planning phase significantly changes the deployment for energy efficient wireless access networks especially for $\delta < 0.3$. The reason is, as we deploy more BSs, we transition from fewer medium-loaded cells to many lightly-loaded cells.

Finally, Fig. 3 displays how the new energy efficient network incorporating cell DTX performs with respect to the daily area power consumption. To this end, we illustrate three distinct cases; 1) blue bar (Case 2): Network deployment without cell DTX; 2) green bar: No Cell DTX considered in the network planning phase, but is in operation; 3) red Bar (Case 1): Network deployment with cell DTX. We observe from Fig. 3 that Cell DTX itself brings striking energy savings (from blue to green bar) even when the network was not planned considering cell DTX. However, designing the network under the assumption that cells can be put into DTX mode during idle state results in additional 42% saving at the cost of deploying around 110 percent more BSs. Furthermore, the resulting network deployment significantly improves the user QoS due to the reduction in overall network load. We can conclude that if the objective is to obtain the maximum energy savings, networks have to be designed taking into account the fact that network deployment and operation are closely related.

V. Conclusion

In this letter, we developed a quantitative method to analyze the impact of cell DTX on network energy consumption. We then used this method to assess the maximal achievable energy saving with this hardware improvement considering the fact that the saving is closely related to initial deployment. To this end, we incorporated cell DTX with the network deployment and obtained the BS density that provides the lowest daily energy consumption satisfying certain coverage and QoS requirements. We showed that, if we take the DTX feature into account already in the planning stage of the network, we can lower the energy consumption with denser deployment of lightly loaded cells. The drawback is the additional deployment cost. In subsequent publications we will therefore investigate the optimum network deployment that minimizes the total network cost considering more realistic deployment scenario with sectorized BSs, various MIMO configurations and heterogeneous cell sizes.

References

[1] E. Oh, B. Krishnamachari, X. Liu, and Z. Niu, “Toward dynamic energy-efficient operation of cellular network infrastructure,” *IEEE Communications Magazine*, vol. 49, no. 6, pp. 56–61, June 2011.

[2] P. Frenger, P. Moberg, J. Malmodin, Y. Jading, and I. Godor, “Reducing Energy Consumption in LTE with Cell DTX,” in *Proc. of IEEE Vehic. Technol. Conf. (VTC Spring)*, Budapest, Hungary, May 2011.

[3] K. Hiltunen, “Total power consumption of different network densification alternatives,” in *Proc. of IEEE Personal, Indoor and Mobile Radio Commun. (PIMRC)*, Sydney, Australia, Sept 2012.

[4] I. Siomina and D. Yuan, “Analysis of cell load coupling for lte network planning and optimization,” *IEEE Transactions on Wireless Communications*, vol. 11, no. 6, pp. 2287–2297, 2012.

[5] M. Imran and et al., “Energy efficiency analysis of the reference systems, areas of improvements and target breakdown,” INFSO-ICT-247733 EARTH,” Deliverable D2.3, Jan. 2012.

[6] 3GPP TR 36.814, “Further Advancements for E-UTRA: Physical Layer Aspects (Release 9),” March 2010.