On the Energy-Bandwidth Trade-off in Green Wireless Networks: System Level Results

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***Abstract*—Energy efficient communication is getting a lot of attention from the industry and academia due to high energy cost of operating mobile networks and their environmental effects. We discuss the self optimization aspect of the mobile network and evaluate the performance of power allocation strategy for the network at low load specifically where bandwidth efficiency is not as important. We propose trading of bandwidth for achieving high energy efficiency. We evaluate the impact of allocation of extra bandwidth in a lightly loaded cell on the overall network energy efficiency. The numerical results demonstrate the optimal load conditions when bandwidth expansion is useful for the network.**

I. Introduction

Traditionally, increase in data rate has been the main focus of research because of ever increasing traffic demands and limited available bandwidth (BW). However, the focus has shifted to energy efficient communication in recent times due to high energy costs of operating a network. A big proportion of the base station sites installed in Africa and Asia are off-grid where diesel consumption enhances the cost sharply. It is predicted that the cost of energy will double by 2020 while 50 percent increase in electricity prices will triple it [1]. In a mobile network, base stations alone are responsible for 80 percent of network's power consumption [2]. Therefore, a lot of emphasis has been put on the optimized design of base stations and energy efficient power allocation schemes.

High energy consumption in mobile networks has environmental effects as well. The information and communication technology sector is estimated to be responsible for about 2 percent of global CO_2 emissions and the corresponding figure for the mobile networks is 0.4 percent [1]. These economic and ecological factors demand for serious measures to investigate the possibility of energy efficient communication.

A lot of recent studies and projects have focussed on the topic of energy efficient radio communication, called green radio communication. A recent work in [3] provides a very detailed overview of the state of the art research and challenges in the area of green radio communications. Reference [4] provides a good overview of the trade-offs involved in modern communication systems. Spectral efficiency defined as the *system throughput per unit bandwidth* is the well accepted criterion for network optimization. However, it usually conflicts with the recently developed energy efficiency metric which is defined as the *system throughput per unit of energy*. The network optimization should take both of these metrics into consideration in the optimization process. Network site deployment by considering energy efficiency aspect has been discussed in [5] where inter-site distance is optimized to ensure energy efficiency of the network.

In this work, we consider a network scenario where long term average traffic requirements vary considerably over the time horizon e.g. day and midnight situation in an industrial area. We assume that we can track such variations by network traffic statistics collected over time. Traditionally, the network is configured to provide quality of experience (QoE) at full load situations. However, when a network is not fully loaded, network resources are under-utilized and energy efficiency of the network can be improved by reconfiguring some of the parameters of the network. In a lightly loaded system, bandwidth is available and can be exploited to reduce the energy consumption by using low order modulation and coding schemes. We use the bandwidth expansion scheme for a lightly loaded system and evaluate the gain using system level simulations for the Long Term Evolution (LTE) system. This idea has been proposed in [6] but that scheme considers short term perspective. For every user, it is decided in each time slot whether it is useful to expand bandwidth or not. We believe it is hard to implement this scheme on a short term basis for each user because of high complexity. It is more practical when we do it at system level on long term basis. Due to frequency selective fading, it may not be useful to expand bandwidth for some of the users but base station power is saved on long term basis by deciding to expand the bandwidth for every user.

We investigate some additional factors that may limit the performance improvement. The matrix for energy gain in [6] does not take into account the offset power of the base station, which is the power consumed at the base station *independent* of the data transmission. At low load, offset power becomes significant proportion of the overall consumed power of base station. Moreover, power allocation scheme for a low load in a given cell should consider the adverse effects on the neighboring cells to determine the over all network efficiency. We argue that these factors limit the application of power adaptation strategies at low load considerably and must be considered.

The rest of this paper is organized as follows. Section II describes the bandwidth expansion scheme used in this work. Section III explains the propagation and power model employed. We discuss the simulation results in Section IV and Section V concludes with the main contributions of this work.

II. Trading Bandwidth For Energy

The idea of trading bandwidth for energy is not new. Shannon's capacity formula provides the basis of this trade-off. In an additive white Gaussian noise (AWGN) channel, for point to point communication, the relationship between achievable rate R and bandwidth B is described by

$$R = B \log_2(1 + \frac{P}{BN_0 + I}) \tag{1}$$

where P and I denote the signal power and interference power, respectively, and N_0 is the power spectral density of the thermal noise. Trading BW for better energy efficiency makes sense because capacity is linear in BW but logarithmic in power. In the past, the focus has always been to achieve high data rates for a given bandwidth. However, the network operator can exploit the reduced data rate requirements to achieve better energy efficiency by using all of the available bandwidth.

We define the term reduced load with reference to a LTE system.

Definition 1: Reduced load γ is defined as the ratio of the number of physical RBs required by the system to meet the traffic demands (without bandwidth expansion) to the total number of RBs available.

We use load in percentage here. In LTE, we have 100 RBs available, each with bandwidth of 180 KHz. For example, if 50 of RBs are in use, the system is operating at 50 percent reduced load.

In a reduced load scenario, a lot of RBs are not in use. We use the idea of bandwidth expansion by assigning more resource blocks to a user than he is assigned if the system operates at (or near) full load.

Definition 2: We define the bandwidth expansion (BE) factor α by the number of RBs allocated after bandwidth expansion for a single RB (without bandwidth expansion) to provide the same rate.

Use of low order modulation and coding scheme helps to reduce the transmit energy and thus, the consumed power of the base station.

BW expansion cannot be employed by any arbitrary factor. At some point, further bandwidth expansion does not save energy anymore. The factor α_{lim} denotes the maximum α which gives significant gain in energy per bit E/b matrix where E and b denote energy in Joule and transmitted bits, respectively.

Thus, for a reduced load γ, the operational expansion factor β is bounded by

$$\beta = \min(1/\gamma, \alpha_{\text{lim}}) \tag{2}$$

The equation states that at reduced load γ, we cannot expand bandwidth more than the minimum of factors α_{limit} and $1/\gamma$. γ is determined from the network traffic at any time and changes over time while α_{lim} represents a fixed system parameter to determine the effective energy gain.

Let S_{av} and S_i denote the mean signal to interference and noise ratio (SINR) of a cell and a RB i, respectively such that

$$S_{\text{av}} = \frac{1}{MN_{\text{RB}}} \sum_{m}^{M} \sum_{i}^{N_{\text{RB}}} S_i^m \tag{3}$$

where N_{RB} is the number of RBs in use in time slot m and M is the window size for averaging SINR over time.

Note that we optimize the user geometry of the system while assuming a specific user distribution. We assume equal achievable rates before and after the bandwidth expansion. Following the framework of [6], for a bandwidth expansion factor α, the average SINR after BW expansion $S_{\text{av}}^{\text{BE}}$ is given by

$$S_{\text{av}}^{\text{BE}} = \sqrt[\alpha]{1 + S_{\text{av}}} - 1 \tag{4}$$

where S_{av} represents the SINR at full load.

III. Simulation Methodology

Our simulation results are based on a long term evolution (LTE) system. The bandwidth of 20 MHz is divided into small frequency blocks, called physical resource blocks (RBs). The bandwidth expansion concept is investigated in a triple-sectored hexagonal cellular network with 21 cells in total, i.e. a center cell surrounded by two tiers of interfering cells. Since we want to evaluate the average behavior of the system, we use a wideband approach where only the path-loss is considered. The path-loss for a distance d is calculated as

$$\frac{L}{\text{dB}} = A + B \cdot \log_{10}\left(\tfrac{d}{\text{m}}\right) + C \cdot \log_{10}\left(\tfrac{f_c}{\text{GHz}}\right) \quad , \tag{5}$$

where the parameters A, B, and C are given in Table I. The channel model does not incorporate fast fading or shadow fading nor certain scheduling strategies. The achievable rates are calculated based on (1). To account for implementation losses, a SINR gap of 3 dB is assumed (i.e., the power P is divided by 2). The mean SINR of a cell is calculated out of its 50% percentile.

Further simulation parameters are provided in Table I. According to our work from [7], we extended the channel model to cover 3-dimensional antenna patterns allowing for an adjustable electrical down tilt angles at the base station antennas. Cell assignment is done by evaluating the center 1 MHz block of the whole signal spectrum, where the primary synchronization signals are located. Hence, the users are always served by the sector whose signal is received with highest average power over the given frequency band. For our evaluations, only users being placed inside the center cell will be considered. In this way, base station signals transmitted from 1st and 2nd tier model the inter-cell interference. The performance is evaluated for different key performance indicators (KPIs).

TABLE I
SIMULATION ASSUMPTIONS.

parameter	value
f_c	2.6 GHz
scenario	urban-macro
path-loss (see (5)): A; B; C	27.155; 35.0413; 23
frequency reuse	1
signal bandwidth	up to 18 MHz, 100 RBs
inter-site distance	500m
number of BS	21 having 3 sectors each
transmit power	up to 43 dBm
sectorization, azimuth diagram	triple, with FWHM of 68°
downtilt angle, elevation diagram	10°, with FWHM of 6.1°
BS height	32m
User height	2m
power model	
a_{ma}; b_{ma}	3.77; 68.73 W
N_{ant}	2

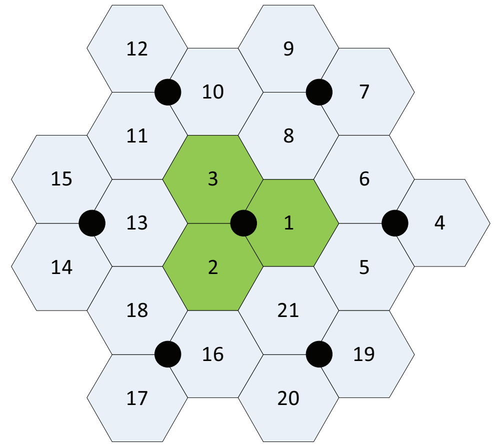

Fig. 1. The structure of the center and border cells under consideration in Scenario 2.

A. Power Model

To calculate the power consumption of base stations, we employ the power model used in [8]. In this model the average consumed power is computed as a linear function of the average radiated power. For a macro base station the average consumed power P_{ma} can be written as

$$P_{\mathrm{ma}} = N_{\mathrm{sec}} N_{\mathrm{ant}} (a_{\mathrm{ma}} P_{\mathrm{tx}} + b_{\mathrm{ma}}) \tag{6}$$

where P_{tx} is the average radiated power of the base station. N_{sec} and N_{ant} denote the number of sectors and number of antennas per sector, respectively. The coefficient a_{ma} accounts for the factors which depend on average radiated power, e.g. power amplifier, cooling of the site etc. The coefficient b_{ma} is independent of the average transmit power and models the offset power due to factors like signal processing, battery backup, etc. [8]. These coefficients are computed from practical experiments and data available for different base station types; and vary for micro and macro base stations. They are given in Table I.

We would like to comment that base station power modeling is an active area of research. The use of power model in [8] is arbitrary. The nature of the results is not dependent on the exact details of the power model as long as the power model represents the active and offset power.

IV. SIMULATION SCENARIOS AND RESULTS

The simulation results are based on two scenarios.

Scenario 1: We assume that all the cells adapt the bandwidth expansion mode (BEM). This assumption is an ideal one but it gives insight into the main concept of bandwidth expansion. We would like to comment here that a lot of work in literature focuses on energy gain by adaptive power control and resource allocation schemes for a single cell and ignores the effects on the border (neighboring) cells. In most of the cases, energy gain in the cell of interest results in a corresponding energy loss in the border cells and this effect needs to be incorporated in the evaluation of results.

Scenario 2: In the second case, only a single cell operates at low load and the rest of the cells have traffic near the full load. This scenario is closer to a practical situation. We set the power of all the border cells to a fixed value required for full load operation and apply bandwidth expansion scheme in the center cell only. We evaluate the performance of the center and the border cells jointly. However, we limit ourselves to the first and second tier of the border cells and neglect the effects on the other cells. A schematic diagram for our evaluation is shown in Fig 1. The center cell consists of the sectors numbered 1, 2 and 3. The border cells are numbered from the sectors 4 to 21.

Any change in transmit power in a given cell due to bandwidth expansion will affect the interference caused on the neighboring cells and this factor must be considered in evaluation. For example, interference per RB decreases in scenario one as a result of the decreased transmit power in the neighboring cells. Similarly, interference per RB decreases in the border cells as a result of decrease in transmit power in the center cell after bandwidth expansion.

In all the results, we assume that the users are uniformly distributed in space. The simulation parameters are based on Table I.

Fig. 2 shows the comparison of the average SINR achieved for the center and border cells for both of the scenarios. For the scenario 1, all the cells operate at the identical load. Therefore, there is no difference between the transmit power of the center and the border cells. It should be noted that there is little improvement in average SINR for the transmit power greater than 40 dBm. The system operates at higher power to account for the indoor penetration loss. As we are interested in evaluating the gain by bandwidth expansion, for a fair comparison, we take 40 dBm as the minimum power required to achieve the required SINR at full load. In scenario 2, when only the center cell operates at low load, the power of the border cells is fixed to 40 dBm (full load). For scenario 2, we plot the SINR for both the center and outer cells as a function of the transmit power of the center cell. Note that in our simulations, the users choose the serving cell based on the *best* available channel as explained in Section III. Therefore, when the power of the center cell is low, the users

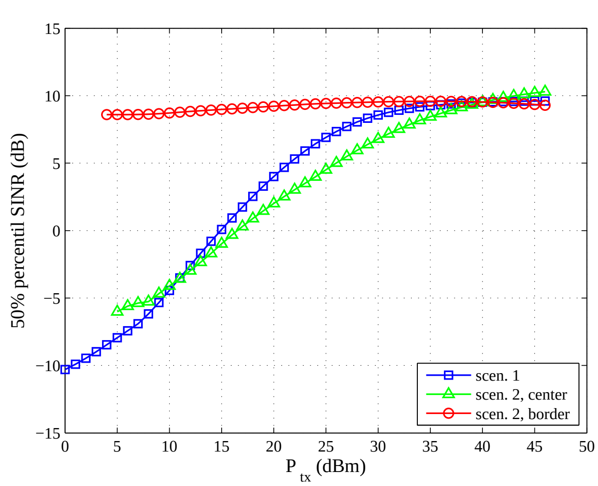

Fig. 2. Comparison of SINR values for the center and border cells for scenarios 1 and 2.

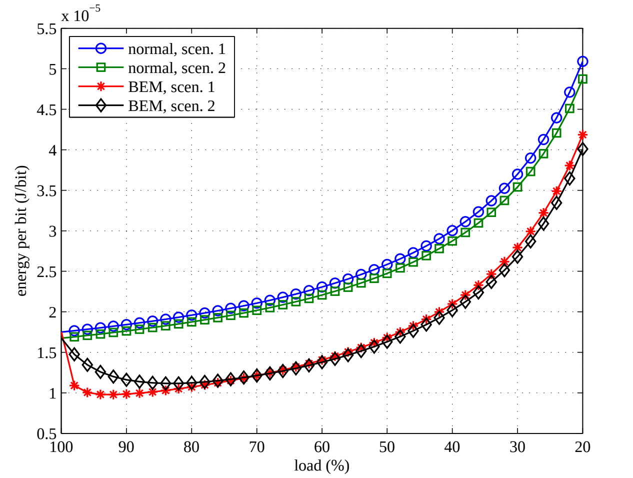

Fig. 4. Energy savings in terms of energy per bit for BE and normal modes using Eq. (6) and power model employed in [8].

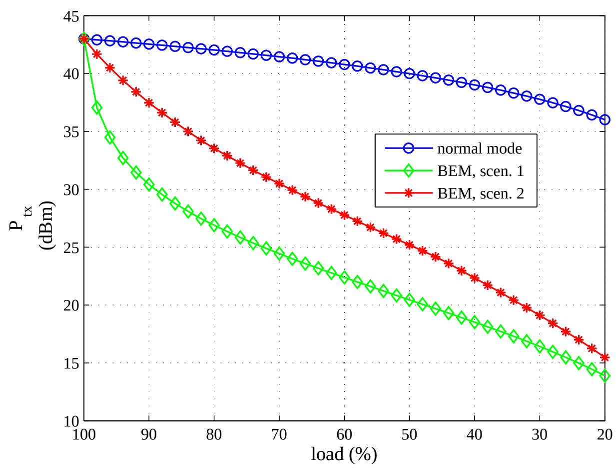

Fig. 3. Transmit power of the center cell for the reduced load γ.

associate themselves with the border (wrong) cells and SINR for the border cells decreases as a result of large path loss experienced. In scenario 2, the users associate themselves with the correct cell in the region when power values of the center cell are similar to the fixed power value of the border cells. The effect due to wrong association of users is usually ignored in most of the studies when only a single cell is simulated. The SINR of the border cells decreases at large transmit power of the center cell because of stronger interference caused by the center cell.

In Fig. 3, we compare the transmit power as a function of the reduced load γ (in percentage) for the different scenarios discussed. In all the simulations, we assume that we expand the bandwidth whenever we have a certain low load $\gamma < 1$ and thus, $\alpha = 1/\gamma$. Fractional bandwidth expansion is possible for the load $0 \leq \gamma < 1$ by allowing a proportion of the users to adapt BE mode in every time slot while the other users operate in normal mode. At $\gamma = 0.5$, transmit power is 3 dBm less than the power at full load for the normal mode as only half of the RBs are in use. However, we observe huge gains in terms of transmit power for both of the cases for $\gamma = 0.5$ (and $\alpha = 2$). The energy gain shows diminishing behaviour for $\gamma < 0.5$ and the incremental gain is very small at small γ. The gain for the scenario 2 is less the gain for the scenario 1 due to large interference caused by the border cells as they operate at full load always and consequently, offer more interference to the users in the center cell as compared to scenario 1.

Fig. 4 illustrates the saving in base station consumed power in terms of energy per bit matrix for the normal and BE modes. The energy consumption is calculated based on the model described in Section III-A with the coefficients taken from [8]. Similar to the results in Fig. 3, we observe a gain in terms of energy per bit initially but it decreases afterwords as the offset power dominates the power consumption of the base station for both of the normal and BE modes.

To quantify the gain from bandwidth expansion scheme more clearly, we define the power gain G_{P} as

$$G_{\mathrm{P}} = 1 - \frac{P_{\mathrm{tx}}^{\mathrm{BE}}}{P_{\mathrm{tx}}^{\mathrm{nor}}} \tag{7}$$

where $P_{\mathrm{tx}}^{\mathrm{BE}}$ and $P_{\mathrm{tx}}^{\mathrm{nor}}$ represent the transmit power with BE mode and normal modes respectively. Similarly, we define the gain in terms of E/b as

$$G_{\mathrm{E/b}} = 1 - \frac{(E/b)^{\mathrm{BE}}}{(E/b)^{\mathrm{nor}}} \tag{8}$$

with $(E/b)^{\mathrm{nor}}$ and $(E/b)^{\mathrm{BE}}$ defining the energy per bit before and after the bandwidth expansion.

Fig. 5 compares G_{P} and $G_{\mathrm{E/b}}$ for different reduced load factors γ. We observe that gain in transmit power increases with load monotonically. However, the gain in energy per bit $G_{\mathrm{E/b}}$ is maximized at a certain reduced load and then decreases for further load reduction. As we use $G_{\mathrm{E/b}}$ a measure of network efficiency, it is not advantageous to increase the BE factor beyond certain limits. We argue that it is not advantageous for scenario 2 to expand BW by more than

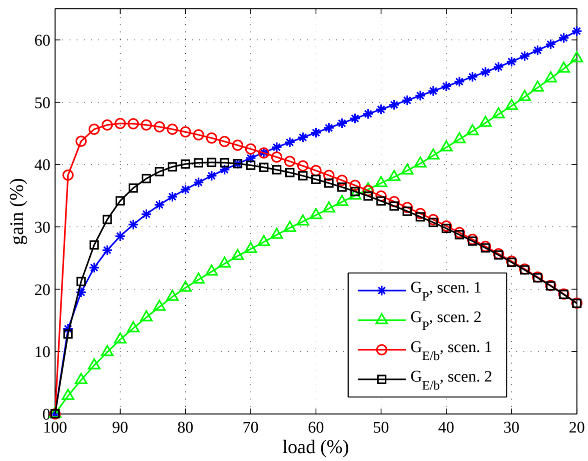

Fig. 5. Comparison of power gain G_{P} and energy per bit gain $G_{(\mathrm{E/b})}$ for the reduced load γ.

$\alpha = 2$ due to an other important observation. As shown in Fig. 2, the SINR in the border cells starts decreasing if we reduce the power of the center cell below 25 dB. Thus, to avoid the performance degradation in the border cells, the center cell must operate at transmit power greater than 25 dBm. From Fig. 3, we observe that the BE factor α equals 2 ($\gamma = 0.5$) at the transmit power 25 dBm. Thus, a further increase in BE factor at the reduced load may seem to provide some gain in the center cell but it will result in a reduced SINR in the border cells. Consequently, the border cells have to increase the transmit power to compensate for this loss in SINR and the overall network efficiency reduces instead. Thus, we conclude that it is not always advantageous to increase the BE factor depending on the reduced load. As we observe in the numerical examples, $\alpha_{\lim}$ in (2) equals 2 as this is the maximum value of α which gives significant gain by network point of view and thus, the operational expansion factor β is bounded by $\min(2, 1/\gamma)$.

A. Discussion on Implementation Considerations

We observe in the numerical results that the offset part of the base station power and the increased energy expenditure in the neighboring cells contribute significantly to reduce the overall network energy efficiency. Thus, the energy gain is not significant at extremely low load conditions. At extremely low conditions, it is always useful to switch off some of the base stations. Switching of the base stations and sleep mode techniques have been extensively studied in literature in the context of green radio networks. However, it is believed that sleep mode techniques are beneficial when the duration of sleep cycles is significant. Otherwise, the frequent switching of some hardware equipment can itself be highly inefficient process. The switching may even require some physical changes at the component level such as mechanical devices to alter the antenna tilt. The authors in [9] discuss the pros and cons of base station switching methods in details.

We argue that bandwidth expansion techniques have their merits when load is moderate and not extremely small. The bandwidth expansion techniques are easy to implement in the conditions when the duration of the low load cycle is small and the network returns back to high load conditions in short time.

V. Conclusion

We investigate the energy efficiency of a wireless network in a lightly loaded system where bandwidth is available and high data rates are not the goal. We propose trading bandwidth with power to make the network more energy efficient. Although the idea is well known in literature, our main contribution is to quantify the limits of bandwidth expansion factor and possible energy gains with LTE system level simulations for the interference model and the scenarios applicable in practical networks. We evaluate the adverse effects of bandwidth expansion on the neighboring cells. We conclude that base station offset power and increased energy expenditure in the neighboring cells limit the use of bandwidth expansion schemes. However, at moderate low loads, bandwidth expansion schemes are still a better option than the sleeping mode techniques due to small implementation complexity.

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