Energy Saving and Capacity Gain of Micro Sites in Regular LTE Networks: Downlink Traffic Layer Analysis *

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ABSTRACT

We study the effect of deployment of low cost, low power micro base stations along with macro base stations on energy consumption and capacity of downlink LTE. [1] studied this problem, using spectral area efficiency as the performance metric. We show that the analysis proposed in [1] is inaccurate as the traffic layer specifications of LTE networks is not included in the analysis. We also investigate the effect of user association and frequency band allocation schemes on energy consumption and capacity of LTE networks.

Specifically, we add the following three important elements to the analysis proposed in [1]: a traffic layer analysis that take both the physical and traffic layer specifications of LTE downlink into account; a threshold-based policy to optimally associate users to base stations; and an allocation scheme to better allocate the frequency band to macro and micro base stations. We investigate all combinations of these elements through numerical evaluation and observe that 1. there are important differences between traffic layer and physical layer analysis, 2. threshold-based user association policy improve the traffic capacity of the network by up to 33% without affecting the energy profile of the network, and 3. considerable energy saving and capacity gain can be achieved thought a careful allocation of the frequency band to macro and micro base stations.

Finally, we determine the optimal network configuration and show that up to 46% saving in energy can be achieved compared to the case that no micro base stations are deployed in the network.

Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]: Wireless communications; C.4 [**Performance of Systems**]: Modeling Techniques

General Terms

Performance

Keywords

LTE networks, energy, performance evaluation

1. INTRODUCTION

Energy consumption of telecommunication networks is not negligible, and wireless networks alone consume approximately 60 billion kWh per year which is about 2% of global CO_2 emission [2]. Predictions show that mobile data traffic will double every year, increasing 39 times between 2009 – 2014 [3]. Hence, future wireless networks must provide more capacity and will, therefore, consume much more energy than today's networks. Thus, there are major environmental and social issues to reduce energy consumption of wireless networks. There is also an important economic incentive for wireless operators to design more energy efficient networks. A published report by Unstrung Insider in 2007 shows that revenue growth of telecom operators is much slower than data traffic growth over their networks [4]. Energy costs account for as much as half of a mobile operators' operating expenses. Hence, it is critical for operators to reduce energy consumption of their networks to decrease their cost.

In this paper, we study the impact of deployment of low cost, low power micro base stations along with macro base stations on energy consumption and capacity gain of wireless LTE networks. Recent studies show that there is a huge potential to reduce energy consumption of LTE networks by using micro base stations to supplement the capacity of the macro cell network [5]. Fehske *et al.* elaborate this

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idea in detail and show that significant energy saving can be achieved through a careful deployment of micro base stations along with macro base stations in a cellular network [1]. The performance metric studied in [1] is area spectral efficiency introduced in [6], which takes only the physical layer data rate into account. However, majority of the traffic in future cellular networks is expected to be elastic traffic composed of data flows. The rate of a flow does not only depend on the physical layer metrics (e.g. spectral efficiency) but also on the number of competing flows in progress and the way the available bandwidth is shared among these flows [7].

We show that the analysis proposed in [1] is inaccurate as the traffic layer specifications of LTE networks is not included in the analysis. We also investigate the effect of user association and frequency band allocation schemes, which have not been considered in [1], on energy consumption and capacity of LTE networks. Specifically , we add the following important elements to the analysis proposed in [1]:

- **E1:** A traffic layer analysis that considers both the physical and traffic layer specifications of LTE downlink (refer to 5). We determine the traffic capacity of the network which is a more appropriate metric than spectral efficiency to model the performance of wireless data networks [8].

- **E2:** A threshold-based user association policy which extends the area served by micro base stations without increasing their transmit power (refer to 3). As macro base stations are usually the bottlenecks, we expect to see higher traffic capacity using this policy.

- **E3:** A frequency band allocation scheme that allocates the frequency band to macro and micro base stations (refer to 4). Note that a full frequency reuse in macro and micro base stations, as used in [1], will cause a high level of interference in the network which is not optimal in term of traffic capacity and energy consumption.

We investigate all combinations of elements **E1**-**E3**. We use a detailed model of the physical layer including shadowing and interference which makes the problem very difficult to be studied analytically. Hence, we perform numerical evaluations. The results show that:

- There is a nonlinear relationship between the number of micro sites per macro cell (N) and the traffic capacity gain. In particular, we observe that out of the scenarios we study $N = 5$ brings much higher capacity gain, irrespective of the other network planning parameters. This differs from the previous findings in [1], which did not consider a traffic layer as we do in **E1**, and found a linear relationship between N and the spectral efficiency gain. The main reason behind this observation is that the traffic capacity corresponds to the harmonic mean of users feasible throughput, while spectral efficiency corresponds to the arithmetic mean of these rates (refer to Section 5.1).

- Threshold-based association policy can improve the traffic capacity of a heterogenous network by up to 33% without affecting the energy profile of the network. Hence, the usual policy that associates users to base stations with best average signal to interference-plus-noise ratio (SINR) is not optimal.

- The optimal frequency band allocation scheme, among those we study in this paper, consists in allocating a fraction of the frequency band to both macro and micro sites and dividing the rest of the frequency band between macro and micro sites. We show for a specific scenario that using our frequency band allocation scheme 20% saving in energy and 10% gain in traffic capacity can be achieved as compared to a full frequency reuse between macro and micro sites.

Finally, we determine though numerical evaluation the optimal network configuration that minimizes the energy consumption in the network for a 30 $Mbits/s/km^2$ target traffic capacity. As control parameters we consider the macro inter site distance, the density and the transmit power of micro sites, the fraction of the frequency band allocated to macro and micro sites, and the threshold-based user association policy parameter. The results show that 46% saving in energy can be achieved compared to the case that no micro sites are deployed in the network.

Our work thus differs from [1], as we add important elements **E1**-**E3** to our study. Moreover, it differs from [9, 10], as similar to [1], only physical layer metrics such as spectral efficiency and SINR are studied in [9, 10]. In [7] a different network configuration where only macro base stations are deployed is considered. Besides, [7] does not study the energy profile aspect of a network and uses an abstracted model for the physical layer.

2. NETWORK MODEL AND ASSUMPTIONS

We use the network and physical layer models similar to the models used in [1] with important modification on the way we calculate the average received power to be more consistent with [11]. We consider a two-tier multi-cell urban environment composed of 19 hexagonal cells as depicted in Figure 1, where the distance between neighboring cells is denoted by D and the area of the reference cell at the center is denoted by $\mathcal{A}$. Two types of base stations are deployed in the network: macro base stations which cover large areas and micro base stations which have a relatively small transmission range. Each cell is partitioned into three macro sectors where each sector is served by a macro base station positioned at the center of the hexagonal cell using directional antennas. The bore-sight of the directional antennas point towards the flat sides of the cell (see Figure 2).

As depicted in Figure 1, micro base stations are deployed at locations in the hexagonal cells where the received signal level from the macro base stations is expected to be relatively low. We consider different network configurations with different average numbers of micro base stations per cell (N). Unlike macro base stations, micro base stations are equipped with omnidirectional antennas. We assume that micro base stations do not contribute to the coverage of macro base stations. The transmit power of macro base stations are then determined such that they provide full coverage in the network (refer to 2.2).

We use the notation $\mathcal{B} = \mathcal{B}_{\text{mi}} \cup \mathcal{B}_{\text{ma}}$ for the set of all base stations in the network where the subsets $\mathcal{B}_{\text{ma}}$ and $\mathcal{B}_{\text{mi}}$ are the set of all macro base stations and the set of all micro base stations, respectively. Since the cellular network is symmetric, restricting the study on the reference area $\mathcal{A}$ only provides results which can be reproduced for other parts of the network. The reference area $\mathcal{A}$ is served by three co-

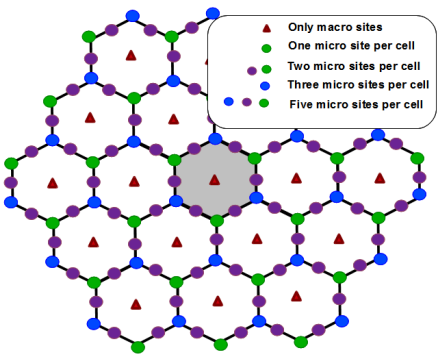

Figure 1: A two tier heterogenous cellular network with different deployment strategies. Micro base stations are positioned at locations where signal strength from macro base stations is expected to be weak.

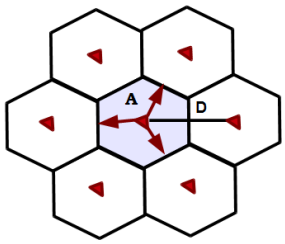

Figure 2: A regular hexagonal network with three sectors per cell, a reference cell of area $\mathcal{A}$ and inter-cell distance D. The three sectors are served by collocated directional macro-base-station antennas.

located macro base stations serving the three sectors and is further covered partially by one or more micro base stations depending on the configuration we choose.

This paper studies the downlink traffic of LTE networks only assuming uplink traffic is of secondary importance for web browsing and video streaming users. However, studying the uplink can be an issue depending on how the spectrum or time is shared between uplink and downlink traffic. It is not possible to ignore the case where the uplink would be the bottleneck. In fact, a good engineering policy would be to balance resources between uplink and downlink. Further, operators may be interested in restricting uplink capacity to reduce the amount of peer to peer traffic.

2.1 Channel model

The quality of the signal transmitted over a wireless channel is affected by several factors such as deterministic path-loss, random shadowing, random multipath fading, penetration loss, and antenna pattern in the case of directional antennas. In what follows, we provide a detailed description of each of these factors and explain how to aggregate their effects to calculate the signal level at a receiver. A more detailed description of our model can be found in the 3GPP specification, [11].

2.1.1 Path loss

Path loss is the attenuation of a signal's power as it propagates through the space. Let r be the distance between transmitter and receiver, then

Urban macro cell	η	$-10\log_{10}\Delta$	$\sigma_{10\log_{10}\Psi}$
LOS ($r < 384$ m)	2.20	35.60	4
LOS ($r \geq 384$ m)	4.00	−10.90	4
NLOS	3.91	17.40	6
Urban micro cell	η	$-10\log_{10}\Delta$	$\sigma_{10\log_{10}\Psi}$
LOS ($r < 144$ m)	2.20	35.60	3
LOS ($r \geq 144$ m)	4.00	−3.20	3
NLOS	3.67	32.60	4

Table 1: Propagation parameters based on [11].

$$PL_{\mathrm{dB}}(r) = \Delta_{\mathrm{dB}} + \eta \cdot 10 \cdot \log_{10} r$$

where $PL_{\mathrm{dB}}(r)$ is the path loss in decibel and Δ is a parameter that encompasses the effects of carrier frequency, receiver and transmitter antenna heights, and other propagation environment factors. η is the path loss exponent which indicates the rate at which the path loss increases with the distance.

As shown in Table 1, the values of η and Δ depend on line-of-sight (LOS) conditions and on whether or not the distance from the transmitter to the receiver is larger than the break point distance (r_b). For urban scenarios, the probability that a user at a distance r from a macro base station has a LOS reception is

$$P_{\mathrm{LOS}}^{\mathrm{ma}}(r) = \min\left\{\frac{18}{r}, 1\right\}(1 - e^{-\frac{r}{63}}) + e^{-\frac{r}{63}}.$$

For a micro base station, the probability is expressed as

$$P_{\mathrm{LOS}}^{\mathrm{mi}} = \min\left\{\frac{18}{r}, 1\right\}(1 - e^{-\frac{r}{36}}) + e^{-\frac{r}{36}}.$$

The break point distance is a function of carrier frequency (f_c), speed of light in free space (c), effective antenna height of the base station (h'_b), and effective antenna height of the user equipment (h'_u):

$$r_b = 4h'_b h'_u f_c / c.$$

We set $h'_b = h_b - 1$ and $h'_u = h_u - 1$ where h_b and h_u are the actual antenna heights of the base station and the user equipment, respectively. h_b is equal to 25 m for macro base stations and 10 m for micro base stations and h_u is assumed to be 1.5 m [11].

2.1.2 Slow fading (Shadowing)

In urban cellular wireless networks, where the environment is characterized by tall buildings and other obstacles, the channel quality is affected by shadowing of the line-of-sight path. Shadowing causes slow fading of the channel quality such that the channel variation is slower than the baseband signal variation. The random shadowing variable, denoted by Ψ, is generally modeled as lognormal distributed such that $10\log_{10}\Psi$ follows a zero mean Guassian distribution [1, 6]. The standard deviation ($\sigma_{\Psi_{\mathrm{dB}}}$) of the Gaussian variable $\Psi_{\mathrm{dB}} = 10\log_{10}\Psi$ has different values for different line-of-sight conditions.

2.1.3 Fast fading (Multipath fading)

Fast fading occurs due to reflection, scattering, and diffraction of signal components by local objects. The received

signal is the superposition of a number of these signal components which may sum up in a constructive or destructive manner depending on the relative phase shift. Employing an efficient diversity-combining antenna at the receiver can eliminate the effect of multipath fading [6]. We do not consider the effect of multipath fading. However, we assume a fast fading margin of 3 dB in the link budget when we compute the receiver sensitivity value introduced in Section 2.2.

2.1.4 Penetration loss

In addition to path loss, shadowing and multipath fading, another factor which affects the channel quality is the outdoor-indoor penetration loss, denoted by κ. In line with assumptions in [11], we use an outdoor-indoor penetration loss of 20 dB. Moreover, the probability that a mobile user is located indoors is assumed to be 0.5.

2.1.5 Antenna radiation pattern

The antenna radiation pattern models the angular dependence of the radiation from the transmitter to the receiver. This paper considers only the horizontal antenna pattern, A_{h}, as proposed in [11], with

$$A_{\mathrm{h}}(\theta) = -\min\left\{12\left(\frac{\theta}{\theta_{3\mathrm{dB}}}\right)^2, A_{\mathrm{m}}\right\} \tag{1}$$

where $\theta \in [-180\ degrees, 180\ degrees]$ is defined as the angle between the direction of interest and the bore-sight of the antenna. $\theta_{3\mathrm{dB}}$ is the 3 dB beam-width in degrees, and A_{m} is the maximum attenuation. For the three-sector scenario, we set $\theta_{3\mathrm{dB}} = 70$ degrees and $A_m = 30$ dB. The antenna pattern values for micro base stations are considered to be 0 dB as they deploy omni-directional antennas.

2.1.6 Calculation of the received power

We denote by

$$\varpi(\theta, r) = PL_{\mathrm{dB}}(r) + \kappa_{\mathrm{dB}} + A_{\mathrm{h}}(\theta).$$

the aggregate signal attenuation factor due to path loss, outdoor-indoor penetration loss, and radiation pattern. The received power, Pr, from a base station at a distance of r and angle θ from the main lobe of the antenna can be calculated as

$$Pr(\theta, r, \Psi) = Pt_{\mathrm{eff}} - \varpi(\theta, r) + \Psi_{\mathrm{dB}} \tag{2}$$

where Pt_{eff} is the effective transmitted power in decibels and Ψ is the lognormal shadowing variable.

2.2 Cell coverage and power consumption model

The effective transmit power of a base station depends on the size of the covered area and the degree of coverage required. We define degree of coverage ζ of a cell as the fraction of a cell of area $\mathcal{A}_{\mathrm{c}}$ where the receive power per subcarrier is greater than a given level $P_{\min}$, i.e.

$$\zeta = \frac{1}{|\mathcal{A}_{\mathrm{c}}|}\int_{\mathcal{A}_{\mathrm{c}}} r \cdot \mathbb{P}(Pr(r, \theta, \Psi) \geq P_{\min})\mathrm{d}r\mathrm{d}\theta, \tag{3}$$

where the operator $\mathbb{P}$ denotes the probability. $P_{\min}$, also known as the receiver sensitivity, is a target minimum received power level below which performance becomes unacceptable [12]. The target minimum received power level depends on thermal noise, noise figure of a mobile terminal, fast fading margin, inter-cell interference margin, and required SNR values among other factors. This paper uses $P_{\min}$ per subcarrier equal to -120 dBm.

Combining (2) and (3), the coverage ζ can be evaluated as

$$\zeta = \frac{1}{|\mathcal{A}_{\mathrm{c}}|}\int_{\mathcal{A}_{\mathrm{c}}} r \cdot Q\left(\frac{P_{\min} - Pt_{\mathrm{eff}} + \varpi(\theta, r)}{\sigma_{\Psi_{\mathrm{dB}}}}\right)\mathrm{d}r\mathrm{d}\theta, \tag{4}$$

where $Q(x)$ is the probability that a standard normal random variable will obtain a value greater than x and $\sigma_{\Psi_{\mathrm{dB}}}$ is the standard deviation of the Gaussian variable Ψ_{dB}. $P_{\min}$ and Pt_{eff} are in dB [12].

We compute Pt_{eff} of the macro and micro base stations by numerically inverting (4). We assume that micro base stations do not contribute to the coverage of macro base stations, i.e. the effective transmit power of a macro base stations is determined such that it provides ζ coverage to the hexagonal cell irrespective of the presence of micro base stations. For the sake of simplicity, we assume that a macro cell has a a circular shape of radius $D/\sqrt{3}$, where D is the distance between two neighboring macro base stations. The effective transmit power of a micro base stations is computed such that it gives ζ coverage to a circular cell of radius R_{mi}. In this paper, the transmit power of a micro base stations is considered as a network planning parameter and the traffic capacity of the network (refer to Section 5.1) is determined for different transmit power levels.

Note that the effective transmit power per subcarrier obtained from (4) is the Equivalent Isotropically Radiated Power in dBi (EIRP), i.e., it is the the emitted transmission power of a theoretical isotropic antenna to produce the same peak power density as in the direction of the maximum antenna gain. The actual total transmitted powers of a macro-base-station antenna and a micro-base-station antenna can be calculated from the corresponding Pt_{eff} values and the parameters of the frequency band allocation scheme (refer to Section 4) by applying a link budget formula. We assume a fully loaded network where macro and micro have always data to send, i.e. the traffic load at macro and micro base stations is very close to one (refer to Section for a justification of our assumption 5.1).

Once the actual transmitted powers are calculated, the energy profile of the network can be determined using an appropriate power consumption model. This paper uses the linear power consumption models given in (5) and (6), which are the same models as proposed in [1]:

$$\mathcal{P}_{\mathrm{ma}} = a_{\mathrm{ma}} \cdot Pt_{\mathrm{ma}} + b_{\mathrm{ma}} \tag{5}$$

$$\mathcal{P}_{\mathrm{mi}} = a_{\mathrm{mi}} \cdot Pt_{\mathrm{mi}} + b_{\mathrm{mi}} \tag{6}$$

where $\mathcal{P}_{\mathrm{ma}}$ and $\mathcal{P}_{\mathrm{mi}}$ denote the power consumption for a macro and a micro base station, respectively, and Pt_{ma} and Pt_{mi} are the actual transmitted powers (in watt) of a macro-base-station antenna and a micro-base-station antenna, respectively. The coefficients a_{ma} and a_{mi} account for the power consumption which scales with the transmitted power whereas b_{ma} and b_{mi} are power offsets consumed independent from the transmitted power [1].

3. THRESHOLD-BASED USER ASSOCIATION POLICY

User to base station association decision is made by the user. The user makes its decisions based on the average SINR it receives from the base stations in the network (if a user decides its association based on the instantaneous received SINR it might change its associated base station multiple times during its connection, which makes such a scheme unrealistic and costly).

For every possible location $u \in \mathcal{A}$, a user (UE) at location u selects the macro (resp. the micro) base station which yields the best average SINR compared to all macro (resp. micro) base stations. UE is associated with the micro base station if the ratio of the average SINR from the best micro base station to the average SINR from the best macro base station is greater than threshold T, otherwise UE is associated to the macro base station:

1. UE senses the channel.
2. UE estimates the average SINR from each macro and micro base station in the network.
3. (a) UE selects the micro base station which yields the best average SINR compared to all micro base stations.
   (b) UE selects the macro base station which yields the best average SINR compared to all macro base stations.
4. If the ratio of the best average SINR from the micro base station to the best average SINR from the macro base station is greater than threshold T then UE is associated with the micro base station; else, UE is associated with the macro base station.

T is considered as a network design parameter and is chosen such that it maximizes the traffic capacity (refer to Section 5.1). Using classic user association policies, as proposed in [11], T is set to one which is not optimal in term of traffic capacity and energy consumption as we show in Section 6.

Applying the above association procedure, each point u in the reference area $\mathcal{A}$ is associated with a base station $i \in \mathcal{B}$. Let $\mathcal{A}_{\mathrm{i}}$ be the set of all locations $u \in \mathcal{A}$ such that a user at location u is associated with base station $i \in \mathcal{B}$. It can be shown that the following conditions hold: $\cup_{i\in\mathcal{B}} \mathcal{A}_i = \mathcal{A}$ and $\mathcal{A}_i \cap A_j = \emptyset$ for all $\forall i, j \in \mathcal{B}$ and $i \neq j$.

4. FREQUENCY BAND ALLOCATION SCHEME

Interference is a big problem in cellular networks. Different frequency band allocation schemes have been proposed in the past to minimize the effect of interference and increase the resource utilization of a network. This paper proposes a simple frequency band allocation scheme to show how a careful allocation of the usable frequency band between the macro and micro sites can effect the energy consumption and traffic capacity of the network.

We assume that the base station antennas for all macro base stations (including those in the same cell) use the same frequency band. We also assume all micro base stations to use the same frequency band which may partially or fully overlap with the frequency band used by macro base stations

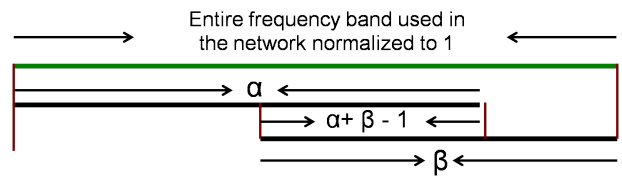

Figure 3: α and β are fractions of frequency band allocated to macro and micro base stations, respectively. $(\alpha + \beta - 1)$ is the fraction of frequency band that is jointly allocated to macros and micros.

as depicted in Figure 3. The particular fraction of bandwidth available for macro and micro base stations, denoted by α and β, are chosen such that they maximize the overall system capacity while minimizing the power consumption of the network.

4.1 Feasible Throughput

A user in a network experiences different levels of interference depending on which portion of the frequency band it is using and depending on which interfering base stations are active. This paper assumes a full buffer scenario where there is always data available at every base station to be transferred in the downlink, i.e., every base station antenna transmits data all the time over its entire frequency band (we will justify this assumption in Section 5.1). Note that due to the three-fold sectorization of macro cells, every base station serving a sector of a macro cell other than the base station which the user is associated with contributes to the interference experienced by the user.

Assume there is an active user at location $u \in \mathcal{A}_{\mathrm{i}}$, $i \in \mathcal{B}$. We determine the instantaneous feasible throughput (data rate) the user can get when there is no other active user in cell $\mathcal{A}_i$. As a result of the frequency band allocation scheme proposed above, the user experiences different levels of interference on different portions of the frequency band. The SINR using the frequency band which is jointly allocated to macro and micro base stations is

$$\gamma_{i,1}(u,\Psi) = \frac{Pr_i(u,\Psi_i)}{\sum_{j\in\mathcal{B}\setminus\{i\}} Pr_j(u,\Psi_j) + \sigma^2} \tag{7}$$

where σ^2 denotes the thermal noise, $Pr_i(u,\Psi_i), i \in \mathcal{B}$ is the desired instantaneous received signal, and $Pr_j(u,\Psi_j)$ $j \in \mathcal{B}, j \neq i$ is the instantaneous received signal from an interfering base station j. $Pr_i(u,\Psi_i)$, $Pr_j(u,\Psi_j)$, and σ^2 are all in *watts/hertz*.

If $i \in \mathcal{B}_{\mathrm{ma}}$, then the SINR over the part of the spectrum which is allocated exclusively to macro base stations is

$$\gamma_{i,2}(u,\Psi) = \frac{Pr_i(u,\Psi_i)}{\sum_{j\in\mathcal{B}_{\mathrm{ma}}\setminus\{i\}} Pr_j(u,\Psi_j) + \sigma^2}. \tag{8}$$

Whereas if $i \in \mathcal{B}_{\mathrm{mi}}$, then the SINR over the frequency band which is assigned only to micro base stations is

$$\gamma_{i,3}(u,\Psi) = \frac{Pr_i(u,\Psi_i)}{\sum_{j\in\mathcal{B}_{\mathrm{mi}}\setminus\{i\}} Pr_j(u,\Psi_j) + \sigma^2}. \tag{9}$$

Let W be the total available frequency band. If $i \in \mathcal{B}_{\mathrm{ma}}$, the instantaneous feasible throughput at location u is

$$\begin{aligned} R_i(u,\Psi) &= (\alpha+\beta-1)W \min\{\log_2(1+\gamma_{i,1}(u,\Psi)), S_{\max}\} \\ &+ (1-\beta)W \min\{\log_2(1+\gamma_{i,2}(u,\Psi)), S_{\max}\}. \end{aligned}$$

Otherwise, if $i \in \mathcal{B}_{\text{mi}}$, the instantaneous feasible throughput at location u will be

$$\begin{aligned} R_i(u,\Psi) &= (\alpha+\beta-1)W\min\{\log_2(1+\gamma_{i,1}(u,\Psi)), S_{\max}\} \\ &+ (1-\alpha)W\min\{\log_2(1+\gamma_{i,3}(u,\Psi)), S_{\max}\}. \end{aligned}$$

If $(\alpha+\beta-1) < 0$, i.e. if there is no overlap between frequency band allocated to macro and micro base stations, the first term in above equations would be zero. LTE supports QPSK, 16-QAM and 64-QAM modulation formats in the physical downlink shared channel. The maximum achievable data rate using a 64-QAM modulation format is 6 bits/sec/Hz, thus, we assume $S_{\max} = 6$ bits/sec/Hz.

Note that the feasible throughput is a decreasing convex function of interference. Hence, if we average over interference and then use this average interference to calculate the feasible throughput, as used in [7] and many other literatures, we will underestimate the feasible throughput of the users.

5. TRAFFIC LEVEL ANALYSIS

We assume users in the reference area $\mathcal{A}$ to generate data requests (for example, ftp downloads and web browsing) randomly according to a poisson process of intensity λ. The probability that a random request is generated in an infinitesimal disk $\mathrm{d}u$ around $u \in \mathcal{A}$ is given by $\delta(u)\mathrm{d}u$ such that $\int_{\mathcal{A}} \delta(u)\mathrm{d}u = 1$. The fraction of request arrivals in subarea $\mathcal{A}_i \subseteq \mathcal{A}$ is given by $\delta_i\lambda$ where $\delta_i = \int_{\mathcal{A}_i} \delta(u)\mathrm{d}u$.

Let $N_i(t)$ be the number of active users in subarea $\mathcal{A}_i$ at time t. We assume a fair sharing of the available LTE resource blocks among all active users being served by base station i [7]. Therefore, the instantaneous actual data rate which an active user at location $u \in \mathcal{A}_i$ would get is $\frac{R_i(u,\Psi)}{N_i(t)}$ where $R_i(u,\Psi)$ is the instantaneous feasible throughput at location u when the channel shadowing state is Ψ.

The number of active users in subarea $\mathcal{A}_i \subseteq \mathcal{A}$ behaves as the number of customers in a multi-class product form queuing network with a processor sharing service discipline [13, Ch. 8]. The class of a customer is defined by u, the position of the customer relative to the associated base station as well as Ψ, the random channel variation due to shadowing. Thanks to the *insensitivity* property of multi-class processor sharing queuing models, the stability of this apparently complex system can be analyzed without knowing the fine traffic statistics [8, 14].

5.1 Stability analysis and traffic capacity

We assume that a user who submits a request stays in its position until the request is fully served. The average service time required to serve a request of mean size Ω bits submitted from $u \in \mathcal{A}_i$ is

$$\tau_i(u) = \int_{\Psi} \frac{\Omega}{R_i(u,\Psi)} f(\Psi)\mathrm{d}\Psi \tag{10}$$

where $f(\Psi)$ is the probability density function of the log-normal distributed variable Ψ. Therefore, the mean of the service times of requests generated from all possible locations in subsystem $\mathcal{A}_i$ is computed as

$$\tau_i = \frac{1}{\delta_i}\int_{\mathcal{A}_i}\left[\int_{\Psi} \frac{\Omega}{R_i(u,\Psi)} f(\Psi)\mathrm{d}\Psi\right]\delta(u)\mathrm{d}u \tag{11}$$

For a product form queuing network with processor sharing queues, the stability condition is the natural condition [13, Ch. 8]. Therefore, for subsystem $\mathcal{A}_i$ to be stable, i.e., for the number of active users being served by base station $i \in \mathcal{B}$ not to grow indefinitely, the following condition has to be satisfied:

$$(\delta_i\lambda)\tau_i = \lambda\Omega\int_{\mathcal{A}_i}\left[\int_{\Psi} \frac{f(\Psi)}{R_i(u,\Psi)}\mathrm{d}\Psi\right]\delta(u)\mathrm{d}u < 1. \tag{12}$$

Let

$$C_{\mathcal{A}_i} = \left(\int_{\mathcal{A}_i}\left[\int_{\Psi} \frac{f(\Psi)}{R_i(u,\Psi)}\mathrm{d}\Psi\right]\delta(u)\mathrm{d}u\right)^{-1}. \tag{13}$$

From (12), we have $\lambda\Omega < C_{\mathcal{A}_i}$. Note that $\rho = \lambda\Omega$ is the traffic intensity in the reference area $\mathcal{A}$. Hence, the maximum achievable traffic intensity in the network (i.e. the traffic capacity) is given by

$$C = \rho_{max} = \min_{i\in\mathcal{B}'}(C_{\mathcal{A}_i}) \tag{14}$$

where $\mathcal{B}'$ is the set of all $i \in \mathcal{B}$ such that $\mathcal{A}_i$ is nonempty.

To derive (14), we used the assumption that every base station transmits data all the time over its entire frequency band. This assumption is valid as 1. we study the heavy traffic regime, and 2. applying optimal association policy we guarantee that $C_{\mathcal{A}_i} = C_{\mathcal{A}_j}$ for all i and j and hence all base stations in the reference area have similar traffic load. 1 and 2 together imply that the traffic loads of all base stations are very close to one. We observe from (12) and (14) that the traffic capacity corresponds to the harmonic mean of the instantaneous feasible throughput of the users in the area, while spectral efficiency corresponds to the arithmetic mean of these feasible throughput [1, 6].

5.2 Optimization problem

We denote $\mathcal{C}_{\text{area}} = \frac{\mathcal{C}}{|\mathcal{A}|}$ the traffic capacity per unit area and by $\mathcal{P} = \frac{\mathcal{P}_{\text{ma}}+N\mathcal{P}_{\text{mi}}}{|\mathcal{A}|}$ the area power consumption of a network, where $\mathcal{C}$ is the traffic capacity in Mbits/s introduced in (14), $|\mathcal{A}|$ is the area of the reference cell in km^2, and N is the average numbers of micro sites per cell.

Our goal is to find an optimal network configuration that yields a traffic capacity per unit area $\mathcal{C}_{\text{area}} \geq \mathcal{C}_{\min}$ with minimum area power consumption, where $\mathcal{C}_{\min}$ is the minimum target traffic capacity per unit area that we wish to achieve. As control parameters we consider the macro inter site distance D, the average number of micro base stations per cell N, transmit power of micro sites R_{mi}, the association policy parameter T, and the fraction of bandwidth available for macro and micro base stations (α and β).

6. SYSTEM EVALUATION

In this section, we numerically evaluate the traffic capacity derived in Section 5.1 and use a brute force technique to solve the optimization problem proposed in Section 5.2. The power consumptions of macro and micro sites are numerically computed as explained in Section 2.2. We use matlab to perform these numerical evaluations.

We consider the two-ring multi-cell heterogenous LTE network depicted in Figure 1. No inter-site cooperation mechanism is used for interference mitigation. We consider a range of inter-cell distance D that varies from 600 m to 2100 m, which is an acceptable range for inter-cell distances using LTE standard [11].

The effective transmit power of a macro base stations is computed using (4) for all possible inter-cell distances such

that the base station provides $\zeta = 95\%$ coverage to the cell. We consider three different effective transmit power levels of a micro base station such that it gives $\zeta = 95\%$ coverage to a circular cell of radius R_{mi} equal to 50, 100, and 150 m.

The values for the power consumption parameters a_{ma}, a_{mi}, b_{ma} and b_{mi} depend on the number of antennas per sector and on the type of antenna used. We use the same values proposed in [1], i.e., $a_{\text{ma}} = 22.6$, $a_{\text{mi}} = 5.5$, $b_{\text{ma}} = 412.4$, and $b_{\text{mi}} = 32.0$. These values are obtained from comparing data of several existing base station types as well as operator's experience for the specific link budget given in [1].

A uniform distribution of users in the reference area $\mathcal{A}$ is assumed. In order to simplify the cumbersome work of integrating over every possible location in the reference area, we partition the cell into a finite square grid of points representing user locations in the cell and use these discrete locations to approximate the reference area.

Numerically evaluating the signal levels from each base station overall possible shadowing effects to compute the SINR value at a certain location in the reference cell is complex. Thus, a Monte Carlo simulation is employed to approximate the shadowing variations. We assume a user experiences on average 200 variations in signal quality during a flow's life time due to random shadowing. The user, therefore, adapts its data rate to serve the flow accordingly. For a given pairs of D and R_{mi}, we use the following steps to simulate the random shadowing effect.
FOR every location $u \in \mathcal{A}$ do

1. Generate 200 samples of Ψ_j from a lognormal distribution for every $j \in \mathcal{B}$.
2. Compute $Pr_j(u, \Psi_j)$ using (2) for every $j \in \mathcal{B}$ and for every sample Ψ_j .
3. Association:
   - Compute the average received signal level from every $j \in \mathcal{B}$ from the $Pr_j(u, \Psi_j)$ values obtained from step 2.
   - Associate u with i for some $i \in \mathcal{B}$ using the association policy in Section 3 and the average signal levels computed in step 3.
4. Compute an array of 200 different $R_i(u, \Psi)$ from the values obtained in step 2.

END
Once the association of every location $u \in \mathcal{A}$ is determined and an array of 200 $R_i(u, \Psi)$ values are computed for every point, we compute the traffic capacity for given values of the parameters α, β and threshold T, using (14) and (13).

6.1 Evaluation results using the same network configuration as in [1]

Figure 4 and Figure 5 shows the area power consumption and the traffic capacity per unit area for different N when the parameters α, β and T are set to 1, and when the transmit power of micro base stations is computed such that it gives a $\zeta = 95\%$ coverage to a circular cell of radius $R_{\text{mi}} = 100$ m. This is the default network deployment strategy when no optimization is made on any of these parameters (this network configuration is used in [1]).

Figures 5 shows the capacity gain increases as N increases. Besides N, the exact positioning of the micro base stations

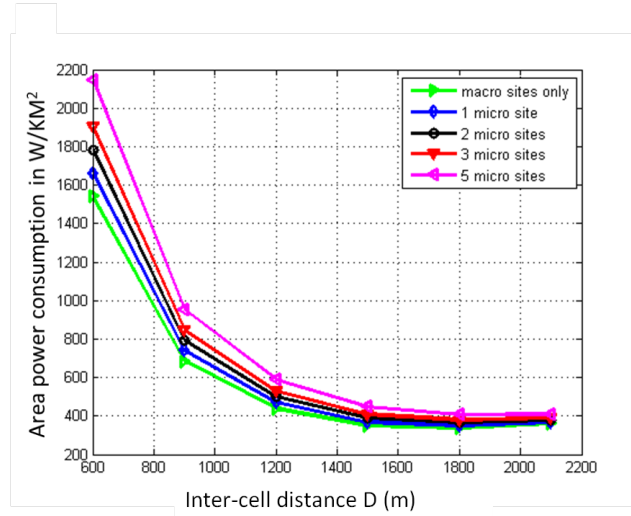

Figure 4: Area power consumption versus D for different N using the same network configuration as in [1], i.e. $\alpha = 1$, $\beta = 1$, $R_{\text{mi}} = 100$ m, and $T = 1$.

affects the amount of capacity gain. In particular, we observe that for $N = 3$ the capacity gain is not as much as it is expected to be. This is because the micro base stations are deployed directly in front of the bore-sight of the macro-base-station antennas. Therefore, the strong interference from the macro base stations on the locations being served by the micro base stations discourages the contribution of the micro base stations to the capacity. Moreover, the subarea covered by a micro base station becomes smaller because many of the locations are associated with the macro base station which provides the largest received signal strength.

6.2 Effect of threshold-based user association policy

In this subsection we seek to characterize the effect of expanding the coverage area of the low-power micro base stations on the traffic capacity of the network without altering their transmit power. The value of the association policy parameter T dictates by how much to expand the micro base stations coverage.

Figure 6 presents the traffic capacity per unit area computed for optimal T values where the parameters α and β are set to 1 and where $R_{\text{mi}} = 100$ m. Table 2 shows the traffic capacities per unit area for a specific macro inter-cell distance $D = 1200$ m. $\mathcal{C}_{area}$ is the traffic capacity per unit area shown in Figure 5 whereas $\mathcal{C}^*_{area}$ is the traffic capacity per unit area obtained for optimal threshold T^*. It is to be noted that varying T value does not affect the area power consumption of the system.

From these results we can infer that choosing an appropriate T value for our association policy significantly increases the capacity of the network without affecting the power consumption. Therefore, the usual user association policy where users associate with the base station having the largest received signal strength is not optimal.

6.3 Importance of traffic layer analysis

The results in [1] show that there is a linear relationship

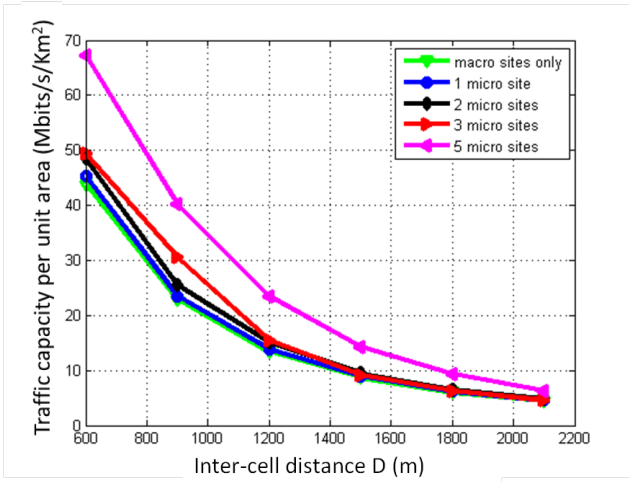

Figure 5: Traffic capacity versus D for different N using the same network configuration as in [1], i.e. $\alpha = 1$, $\beta = 1$, $R_{\mathbf{mi}} = 100$ m, and $T = 1$.

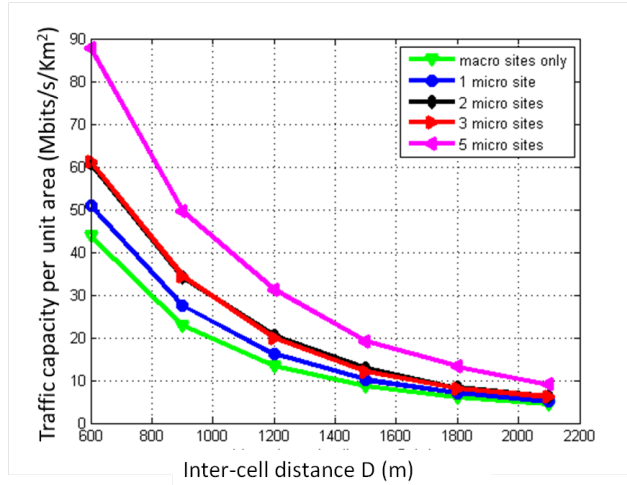

Figure 6: Effect of threshold-based user association policy: we depict traffic capacity per unit area versus D for different N using threshold-based association policy with optimal T, where $\alpha = 1$, $\beta = 1$, and $R_{\mathbf{mi}} = 100$ m.

	number of micro base stations per cell				
	0	1	2	3	5
$\mathcal{C}_{area}$	13.34	13.85	15.02	15.49	23.46
$\mathcal{C}^*_{area}$	13.34	16.11	20.40	19.86	31.23
T^*	-	0.4	0.5	0.7	0.6

Table 2: Effect of threshold-based user association policy: traffic capacity per unit area in Mbits/s/km^2 with $T = 1$ ($\mathcal{C}_{area}$) and with T^* ($\mathcal{C}^*_{area}$) for $\alpha = 1$, $\beta = 1$, $R_{\mathbf{mi}} = 100$ m, and $D = 1200$ m.

between N and the gain in the 10-percentile of area spectral efficiency for a given inter-cell distance. Figure 5 shows the traffic capacity per unit area for the same network configuration as in [1]. Figure 6 presents the traffic capacity per unit area computed using optimal T values when the other network configuration parameters are set as in [1]. Both the results show that there is a nonlinear relationship between N and the capacity gain. Only the strategy with 5 micro base stations per macro cell gives a visible capacity gain. Hence, traffic capacity and spectral efficiency are different metrics which may result in different network planning strategies.

The main reason behind this observation is that the traffic capacity corresponds to the harmonic mean of users feasible throughput, while spectral efficiency corresponds to the arithmetic mean of these rates as shown in Section 5.1.

6.4 Effect of transmit power of micro base stations

Varying the transmit power of micro base stations vary the area served by them. It also affects the area power consumption of the network. In this subsection we present the traffic capacity per unit area and the area power consumption of the network for three different transmit powers of micro base stations. These different transmit powers are computed such that the micro base stations provides $\zeta = 95\%$ coverage to a circular cell of radius 50 m, 100 m and 150 m.

Tables 2(a) shows the traffic capacity per unit area for macro inter-cell distance $D = 1200$ m and for the three different transmit power levels of micro base stations. The traffic capacities per unit area are computed for an optimal value of T that maximizes the traffic capacity for $\alpha = 1$ and $\beta = 1$. Table 2(b) shows the area power consumption.

Though increasing the micro cell radius from 50 m to 100 m meters increases the capacity, there is no much gain in capacity by increasing it farther from 100 m to 150 m. In fact it can lead to a reduction in capacity while increasing the area power consumption. The reduction in capacity is most likely attributed to an increase in interference from micro base stations due to the larger transmit power. Therefore, a transmit power computed for a 100 m cell radius will be used in the following subsections for micro base stations.

6.5 Effect of frequency band allocation scheme

Figure 7 shows the variation in traffic capacity per unit area as a function of α and β where for each α and β the optimal value for T is computed and where $R_{\text{mi}} = 100$ m. We observe that $\alpha = 0.8$ and $\beta = 0.8$ is the strategy that maximizes the capacity. Using this strategy, we achieve 20% saving in energy and 10% gain in capacity compared to a full reuse scheme. Note that, however, the optimal strategy for the optimization problem defined in Section 5.2 is $\alpha = 0.6$ and $\beta = 0.8$ as will be shown in the next section.

6.6 Achieving a target capacity with optimal network deployment strategy

To solve the optimization problem proposed in Section 5.2, we perform a brute force search over values of D from 600 m to 2100 m with steps of 100 m; values of α and β from 0 to 1 with steps of 0.1; values of T from 0 to 2 with steps of 0.1; and $R_{\text{mi}} \in \{50, 100, 150\}$ m. We set target traffic capacity to 30 Mbits/s/km^2.

We find that the optimal network deployment strategy is to set $D = 1200$ m, $N = 5$, $R_{mi} = 100$ m, $\alpha = 0.6$, $\beta = 0.8$ and $T = 0.3$. For this values, we get $\mathcal{C}_{\text{area}} = 32.42\ Mbits/s/\text{km}^2$ and $\mathcal{P} = 517.04\ watt/\text{km}^2$. From Figure 5 and 4, we can see that for a cellular network of only macro base stations $\mathcal{C}_{\text{area}} = 30$ Mbits/s/km^2 can be achieved

(a) Traffic capacity per unit area in Mbits/s/km^2 computed for optimal T for different transmit power levels of micro base stations and for $\alpha = 1$, $\beta = 1$, and $D = 1200$ m.

	number of micro base stations per cell				
	0	1	2	3	5
$\mathcal{C}_{area}(50m)$	13.34	15.24	17.27	16.37	21.58
$\mathcal{C}_{area}(100m)$	13.34	16.11	20.40	19.86	31.23
$\mathcal{C}_{area}(150m)$	13.34	16.02	20.93	20.10	29.22

(b) Area power consumption in watt/km^2 for different transmit power levels of micro base stations and for $\alpha = 1$, $\beta = 1$, and $D = 1200$ m.

	number of micro base stations per cell				
	0	1	2	3	5
$\mathcal{P}(50m)$	438.91	464.81	490.70	516.60	542.49
$\mathcal{P}(100m)$	438.91	469.27	499.62	529.98	560.33
$\mathcal{P}(150m)$	438.91	481.23	523.55	565.86	608.18

Table 3: Effect of transmit power of micro base stations on traffic capacity per unit of area and area power consumption.

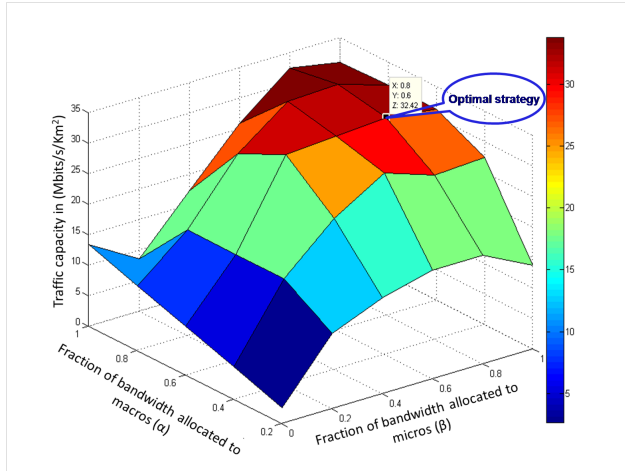

Figure 7: Effect of frequency band allocation scheme: we depict traffic capacity per unit area of a network with $D = 1200$ m computed for optimal T and for different α and β values where $R_{\mathbf{mi}} = 100$ m.

for $D \leq 800$ m that results $\mathcal{P} \geq 968$ watt/km^2. Therefore, the area power consumption improvement by utilizing the optimal deployment strategy described above is

$$\frac{968.5 - 517.04}{968.5} = 46.61\%.$$

This shows that deploying heterogenous networks with intelligent association policy and band allocation scheme considerably improves the power consumption of a network for a given capacity requirement.

7. CONCLUSION

We have studied energy saving and capacity gain of downlink layer of heterogenous LTE networks. Our results show significant energy saving and traffic capacity gain by deploying low power micro base stations and by carefully choosing other network design parameters. We have found that network performance depends strongly on network design decisions like user to base station association policy, bandwidth allocation schemes, micro base station density, and the exact positioning of micro base stations in the network.

As possible extension of this work, we intend to address irregular (random) cellular network topology which is a more realistic scenario in real world cellular networks. We also plan to study a random positioning of micro cells to take care of hotspot locations in a network. It is also important to study the impact of uplink traffic on the over all network performance. The amount of traffic in the uplink can affect our association policy due to the limitations on the level of transmit power of a mobile terminal.

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