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

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Abstract

We study the impact of deployment of low cost, low power micro base stations along with macro base stations on energy consumption and capacity of downlink LTE. We add three important elements to the existing studies: a traffic layer analysis that take both the physical and traffic layer specifications of LTE downlink into account; a threshold-based policy to associate users to base stations; and an allocation scheme to allocate the frequency band to macro and micro sites. We investigate all combinations of these elements through numerical evaluation. We observe that 1. there are important differences between traffic layer and physical layer analysis, 2. threshold-based user association policy improve the 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 an optimal allocation of the frequency band to macro and micro sites. Finally, we show that up to 46% saving in energy can be achieved by a careful network deployment as compared to the case that no micro sites are deployed in the network.

I. 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 [12]. Predictions show that mobile data traffic will double every year, increasing 39 times between $2009 - 2014$ [9]. 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 [15]. 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 operating cost.

In this paper, we focus on saving energy on the radio access part of wireless networks, more specifically on base stations, which represent about 80% of energy costs [14]. 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 [10]. Fehske *et al.* elaborate this 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 [13]. The performance metric studied in [13] is area spectral efficiency introduced in [2], 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 [5]. Hence, physical layer performance metrics such as spectral efficiency and signal to interference noise ratio (SINR), as considered in many papers such as [1], [7], [13], [17], [19], [22], may not be appropriate metrics to model the performance of wireless data networks.

Similar to the model used in [13], we consider a regular hexagonal LTE network, where the locations of micro base stations in the hexagonal cells are chosen such that the received signal level from macro base stations at those locations is expected to be relatively low.We add the following elements to the analysis proposed in [13] that we believe are important:

- **E1:** A traffic layer analysis that takes both the physical and traffic layer specifications of LTE downlink into account (refer to VI). We determine the traffic capacity of the network which we believe is a more appropriate metric than spectral efficiency to model the performance of wireless data networks [4].
- **E2:** A threshold-based user association policy which extends the area served by micro base stations without increasing their transmit power (refer to V). As macro base stations are usually the bottlenecks, we expect to see higher traffic capacity using this policy.
- **E3:** A novel frequency band allocation scheme that allocates the frequency band to macro and micro base stations (refer to IV). Note that a full frequency reuse in macro and micro base stations 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 [13], which did not consider a traffic layer as we do in **E1**, and found a linear relationship between N and the spectral efficiency gain. Hence, traffic capacity and spectral efficiency are different metrics that may result in different network planning strategies.

- 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 levels is not optimal.
- The optimal frequency band allocation scheme is to allocate a fraction of the frequency band to both macro and micro sites and divide 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.

The rest of this paper is structured as follows. In the following section we give a brief overview of the state of the art. Section III describes the network model and assumptions for our study. In Section IV, we propose our traffic layer analysis and we derive the capacity of the network. We also define our energy saving optimization problem. The evaluation results are presented in Section V. Finally, Section VI concludes this paper and discusses possible direction for future work.

II. RELATED WORK

Energy saving in heterogeneous LTE networks consisting of base stations with different energy-performance tradeoffs is studied in [10], [13]. They show that significant energy saving can be achieved by shifting traffic from macro to micro base stations.

The possibility of saving energy by switching off less utilized base stations is investigated in [11], [18]. Park *et al.* consider heterogeneous networks and show that significant energy saving can be achieved by turning off base stations that are less utilized [21]. They use a very abstracted model of physical and traffic layer in their paper. Note that switching off a base station might decrease the level of coverage in the network that is not desirable by operators.

Power control schemes are used for interference, energy, and coverage management in cellular networks to enhance spectral reuse, reduce overall energy consumption, and improve connectivity [8]. Energy saving and spectral efficiency gain of power control schemes in OFDMA-based networks is studied in [19]. In [17], [22], it is shown that improvement in overall power consumption and throughput can be obtained using joint power-frequency allocation mechanisms. *Chen et al.* follow a network planning approach and determine a cell coverage that minimizes power

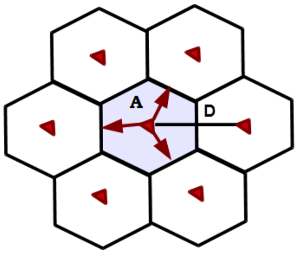

Fig. 1. A regular hexagonal network with three sectors per cell, a reference cell of area $\mathcal{A}$ and inter site distance D. The three sectors are served by collocated directional macro site antennas.

consumption of the network [1]. The performance metrics studied in [17], [19], [22] are physical layer metrics such as bit error rate, SINR, and spectral efficiency.

A traffic layer analysis of the capacity gain of different frequency reuse schemes in the downlink of LTE networks is proposed in [5]. Their results are proposed for different network configurations where only macro base stations are deployed. Moreover, they did not study the energy profile aspect of their network.

III. NETWORK MODEL AND ASSUMPTIONS

The cellular network is modeled as a set of regular hexagonal cells as shown in Figure 1. We consider a two-tier multi-cell urban environment composed of 19 hexagonal cells where the distance between neighboring macro-sites 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 directional macro site antennas positioned at the center of the hexagonal cell. The bore-sight of the directional antennas point towards the flat sides of the cell.

As depicted in Figure 2, 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. Unlike macro base stations, micro base stations are equipped with omnidirectional antennas.

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-located macro base stations serving the three sectors and is further covered partially by one or more micro sites 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

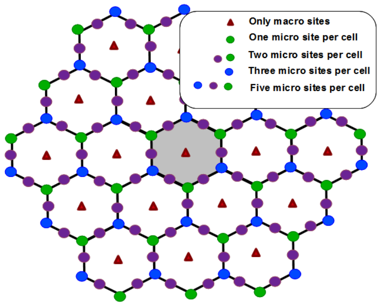

Fig. 2. A two tier heterogenous cellular network with different deployment strategies. Micro base stations are positioned at locations where signal strength from macro base stations is expected to be weak.

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.

A. 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, [20].

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

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

where $PL_{\text{dB}}(r)$ 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 I, 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

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

For a micro base station, the probability is expressed as

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

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):

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

TABLE I

PROPAGATION PARAMETERS BASED ON [20]

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

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 [20].

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 [2], [13]. The standard deviation $(\sigma_{\Psi_{\text{dB}}})$ of the Gaussian variable $\Psi_{\text{dB}} = 10\log_{10}\Psi$ has different values for different line-of-sight conditions.

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 [2]. In this paper, 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 III-B.

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 [20], 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.

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 [20], with

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

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

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.

B. 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.

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

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 [3]. 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

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

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 [3].

We compute Pt_{eff} of the macro and micro sites by numerically inverting (4). We assume that micro sites do not contribute to the coverage of macro sites, i.e. the effective transmit power of a macro site is determined such that it provides ζ coverage to the hexagonal cell irrespective of the presence of micro sites. 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 sites. The effective transmit power of a micro site 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 site is considered as a network planning parameter and the network performance 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

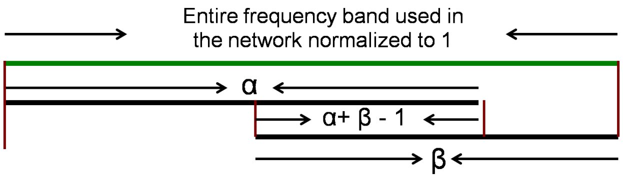

Fig. 3. Fraction of frequency band allocated to macro and micro sites.

a macro site antenna and a micro site antenna can be calculated from the corresponding Pt_{eff} values by applying a link budget formula.

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 [13]:

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

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

where $\mathcal{P}_{\text{ma}}$ and $\mathcal{P}_{\text{mi}}$ denote the power consumption for a macro site and a micro site, respectively, and Pt_{ma} and Pt_{mi} are the actual transmitted powers (in watt) of a macro site antenna and a micro site 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 [13].

IV. 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 that careful allocation of the usable frequency band between the macro and micro sites can further increase system performance. We assume that the base station antennas for all macro sectors (including those in the same cell) use the same frequency band. We also assume all micro sites to use the same frequency band which may partially or fully overlap with the frequency band used by macro sites 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.

V. USER ASSOCIATION POLICY

User equipment to base station association decision is made by the user equipment. The equipment makes its decisions based on the average signal levels it senses from the base stations in the network. For every possible location $u \in \mathcal{A}$, a user equipment (UE) at location u executes the following procedure to decide which base station to associate with:

1) UE senses the channel.
2) UE estimates the average received signal level from each macro and micro site in the network.
3) a) UE selects the micro base station which yields the best average signal level compared to all micro base stations.
    b) UE selects the macro base station which yields the best average signal level compared to all macro base stations.
4) If the ratio of the best average signal from the micro base station to the best average signal 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.

    End

T is chosen such that it maximizes the overall system capacity. Using 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 equipment at location u is associated with base station $i \in \mathcal{B}$. It can be shown that the following conditions hold:

1) $\cup_{i \in \mathcal{B}} \mathcal{A}_i = \mathcal{A}$
2) $\mathcal{A}_i \cap A_j = \emptyset$ for all $\forall i, j \in \mathcal{B}$ and $i \neq j$.

A. 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 the whole available frequency band. Note that due to the three-fold sectorization of macro base stations, 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 $u \in \mathcal{A}_{\mathrm{i}}$, $i \in \mathcal{B}$, who can utilize the entire available resource blocks. 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 in Section IV, the user experiences different levels of interference on different portions of the frequency band. In the following, we first determine the different SINR values. Then we compute the overall feasible throughput as the expected rate using the available frequency band.

The SINR using the frequency band which is jointly allocated to macro and micro base stations is

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

where σ^2 denotes the thermal noise density, $Pr_i(u,\Psi_i), i\in\mathcal{B}$ 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$j$.

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

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

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

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

Let the total available frequency bandwidth be denoted by *W*. If $i\in\mathcal{B}_{\text{ma}}$, the instantaneous feasible throughput at location u is

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

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

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

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 set S_{max} to 6 bits/sec/Hz.

VI. TRAFFIC LEVEL ANALYSIS

In this section, we introduce a traffic level analysis of the downlink layer of an LTE regular hexagonal network. We assume users in the references 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 du around $u\in\mathcal{A}$ is given by $\delta(u)\mathrm{d}u$ such that $\int_{\mathcal{A}}\delta(u)\mathrm{d}u=1$. Therefore, the fraction of request arrivals in subarea $\mathcal{A}_i\subseteq\mathcal{A}$ is given by $\delta_i\lambda$ where,

$$\delta_i=\int_{\mathcal{A}_i}\delta(u)\mathrm{d}u. \tag{10}$$

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 [5]. Therefore, the instantaneous actual data rate which an active user at location $u\in\mathcal{A}_i$ would get is $R_i(u,\Psi)/N_i(t)$ where $R_i(u,\Psi)$ is the instantaneous feasible throughput at location u and when the channel shadowing state is Ψ, as defined in Section V-A.

The state of subarea $\mathcal{A}_i \subseteq \mathcal{A}$ with $N_i(t)$ active users can be defined by a vector $X_i(t)$ that contains the position of each active user and the instantaneous shadowing seen by each active user. 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 [16, 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 [4], [6]. As shown in [5], the figure of merit required to analyze the stability conditions and the capacity of the system is the average service time.

A. Stability analysis and system capacity

We assume that a user which 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

$$\tau_i(u) = \int_{\Psi} \frac{\Omega}{R_i(u,\Psi)} f(\Psi)\mathrm{d}\Psi \tag{11}$$

where $f(\Psi)$ is the probability density function of the lognormal 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

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

A queuing system is said to be stable if the distribution of the queue sizes has a stationary distribution; for a product form queuing network, this is true whenever the mean service rate of the system is greater than the rate at which traffic is generated. 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:

$$(\delta_i \lambda)\tau_i = \lambda\Omega \int_{\mathcal{A}_i} \left[\int_{\Psi} \frac{f(\Psi)}{R_i(u,\Psi)} \mathrm{d}\Psi \right] \delta(u)\mathrm{d}u < 1. \tag{13}$$

From this we obtain

$$\lambda\Omega < \left(\int_{\mathcal{A}_i} \left[\int_{\Psi} \frac{f(\Psi)}{R_i(u,\Psi)} \mathrm{d}\Psi \right] \delta(u)\mathrm{d}u \right)^{-1}. \tag{14}$$

Note that $\rho = \lambda\Omega$ is the traffic intensity in the reference area $\mathcal{A}$. The traffic intensity of a network is defined as the amount of traffic in bits per second generated in the network. Hence, the maximum achievable traffic intensity in the network (i.e. the capacity of the network) is given by

$$C = \rho_{max} = \min_{i \in \mathcal{B}'} (C_{\mathcal{A}_i}) \tag{15}$$

where

$$C_{\mathcal{A}_i} = \left(\int_{\mathcal{A}_i} \left[\int_{\Psi} \frac{f(\Psi)}{R_i(u,\Psi)} \mathrm{d}\Psi \right] \delta(u)\mathrm{d}u \right)^{-1} \tag{16}$$

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

B. Optimization problem

We denote

$$\mathcal{C}_{\text{area}} = \frac{\mathcal{C}}{\mathcal{A}} \tag{17}$$

the network capacity per unit area. $\mathcal{C}$ is the system capacity in Mbits/s introduced in (15) and $\mathcal{A}$ is the area of the reference cell in km^2. The area power consumption of a network with an average of N micro sites per cell, as defined in [13], is given by:

$$\mathcal{P} = \frac{\mathcal{P}_{\text{ma}} + N\mathcal{P}_{\text{mi}}}{\mathcal{A}} \tag{18}$$

where $\mathcal{P}_{\text{ma}}$ and $\mathcal{P}_{\text{mi}}$ are the power consumption of macro and micro sites (in watt), respectively.

Our goal is to find an optimal deployment strategy that yields a network capacity per unit area $\mathcal{C}_{\text{area}} \geq \mathcal{C}_{\text{min}}$ with minimum area power consumption where $\mathcal{C}_{\text{min}}$ is the minimum target 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, the association policy parameter T, and the fraction of bandwidth available for macro and micro base stations (α and β).

VII. SYSTEM SIMULATION

In this section, we first describe the simulation settings then give details of our findings.

A. Simulation settings

For our simulation we consider a two-ring multi-cell heterogenous LTE network depicted in Figure 2. No inter-site cooperation mechanism is used for interference mitigation.

We run the simulation over a range of macro inter site distance D values; specifically from 600 m to 2100 m. LTE networks are expected to satisfy targeted higher data rates. However mobile terminals have limitations on the level of transmit power to achieve such data rates for cell edge users. This constraint on the uplink budget will, therefore, necessitate the need for smaller cell sizes. Thus the range of macro inter site distance values used in this paper are representative for actual urban area LTE networks.

The effective transmit power of a macro site is computed using (4) for all possible inter site distances such that the site 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 m, 100 m, 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. In this paper, we use the same values proposed in [13], 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 Table II.

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 equipment experiences on average 200 variations in signal quality during a flow's life time due to random shadowing. The user equipment, therefore, adapts its data rate to serve the flow accordingly. 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 V 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 system capacity for given values of the parameters α, β and threshold *T*, using (15) and (16).

B. Simulation results

Figure 4 and Figure 5 show the area power consumption and the system capacity per unit area for different number of micro base stations per cell when the parameters α, β and T are set to 1, and when the micro site transmitted power 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 the parameters α, β and T. The results show that merely adding micro sites without any parameter optimization improves the capacity of the network for a given macro inter site distance D. Figures 5 shows the capacity gain increases as the average number of micro sites per cell increases.

Besides the density of micro sites, the exact positioning of the micro sites affects the amount of capacity gain. If we look at the results for three micro sites per cell deployment strategy both in Figures 5 and 6, the capacity gain is not as much as it is expected to be. This is because the micro sites are deployed directly in front of the bore-sight of the macro site antennas. Therefore, the strong interference from the macro sites on the locations being

TABLE II

LTE-BASED LINK BUDGET AND OTHER PARAMETER VALUES

Carrier frequency	2.4 GHz
Bandwidth	5 MHz
Subcarrier spacing B_{sc}	15 KHz
Fast fading margin	2 dB
Inter-cell interference margin	3 dB
Thermal noise	-174 dBm/Hz
SNR required	0 dB
Receiver sensitivity per subcarrier (P_{min})	-120 dBm
Number of antennas (per sector):	
Macro / Micro / MS	$2/1/1$
Number of sectors per cell:	
Macro / Micro	$3/1$
Antenna gain (main lobe):	
Macro / Micro / MS	15 dBi / 2 dBi / -1 dBi
Noise figure:	
Macro / Micro / MS	4 dB / 4 dB / 7 dB
Coverage (both Macro and Micro cells)	95%

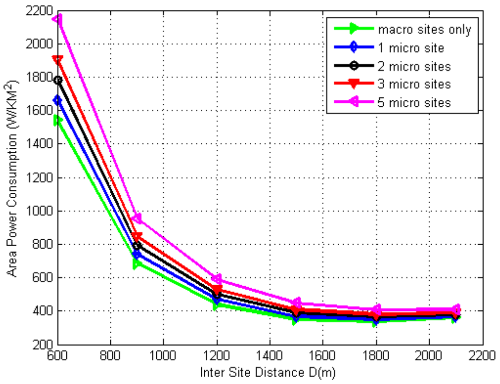

Fig. 4. Area power consumption versus inter site distance for different micro site densities and for $\alpha = 1$, $\beta = 1$.

served by the micro sites discourages the contribution of the micro sites to the network 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.

1) Importance of traffic layer analysis: The results in [13] show that there is a linear relationship between the number of micro sites per cell and the gain in the 10-percentile of area spectral efficiency for a given inter site distance. Figure 5 shows the network capacity per unit area when both macro and micro base stations use the entire bandwidth and when no optimal association policy is implemented. The results show that there is a nonlinear relationship between the number of micro base stations and the capacity gain. Only the strategy with 5 micro sites per macro cell gives a visible capacity gain. Hence the traffic level analysis gives a different performance metric from the physical layer metrics like area spectral efficiency.

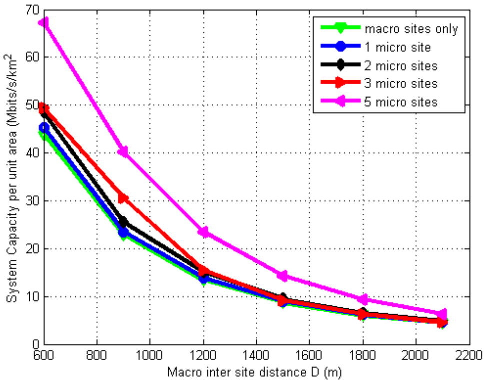

Fig. 5. System capacity per unit area versus inter site distance for different micro site densities and for $\alpha = 1$, $\beta = 1$, $T = 1$.

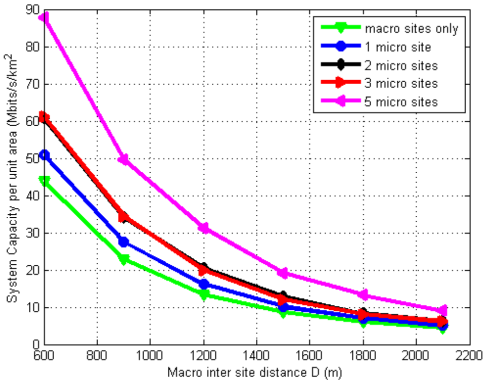

Fig. 6. System capacity per unit area versus inter site distance for different micro site densities computed for optimal T and $\alpha = 1$, $\beta = 1$.

2) Micro site range extension: In this subsection we seek to characterize the effect of expanding the coverage area of the low-power micro sites on network capacity without altering their transmit power. The value of the association policy parameter T dictates by how much to expand the micro site coverage.

Figure 6 presents the system capacity per unit area computed for optimal T values when the parameters α and β are set to 1. The transmit power of micro sites is computed for a circular cell of radius $R_{\mathrm{mi}} = 100$ m. Table III shows the system capacities per unit area for a specific macro inter site distance $D = 1200$ m. C is the system capacity per unit area shown in Figure 5 whereas C^* is the system 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 system capacity without affecting the power consumption. Therefore, the usual user association policy

TABLE III

SYSTEM CAPACITY PER UNIT AREA IN MBITS/S/km^2 WITH AND WITHOUT RANGE EXTENSION.

	number of micro sites per cell				
	0	1	2	3	5
C	13.34	13.85	15.02	15.49	23.46
C^*	13.34	16.11	20.40	19.86	31.23
T^*	-	0.4	0.5	0.7	0.6

TABLE IV

SYSTEM CAPACITY PER UNIT AREA IN MBITS/S/km^2 COMPUTED FOR OPTIMAL T FOR DIFFERENT MICRO SITE TRANSMIT POWER LEVELS, $\alpha = 1$, $\beta = 1$.

	number of micro sites per cell				
	0	1	2	3	5
C_1	13.34	15.24	17.27	16.37	21.58
C_2	13.34	16.11	20.40	19.86	31.23
C_3	13.34	16.02	20.93	20.10	29.22

TABLE V

AREA POWER CONSUMPTION IN WATT/km^2 FOR DIFFERENT MICRO SITE TRANSMIT POWER LEVELS, $\alpha = 1$, $\beta = 1$.

	number of micro sites per cell				
	0	1	2	3	5
$\mathcal{P}_1$	438.91	464.81	490.70	516.60	542.49
$\mathcal{P}_2$	438.91	469.27	499.62	529.98	560.33
$\mathcal{P}_3$	438.91	481.23	523.55	565.86	608.18

where users associate with the base station having the largest received signal strength is not optimal.

3) Effect of micro site transmit power: Varying the micro site transmit power varies the area served by micro sites. Moreover, it also affects the area power consumption of the network. In this subsection we present the system capacity per unit area and the area power consumption of the network for three different micro site transmit powers. These different transmit powers are computed such that the micro site provides $\zeta = 95\%$ coverage to a circular cell of radius 50 m, 100 m and 150 m.

Tables IV shows the system capacity per unit area for macro inter site distance $D = 1200$ m and for the three different micro site transmit power levels. The system capacities per unit area are computed for an optimal value of T that maximizes the system capacity. Table V shows the area power consumption of the network for the three different micro site transmit power levels.

Though increasing the micro cell radius from 50 m to 100 m meters increases the system 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 system capacity while increasing the area power consumption. The reduction in capacity is most likely attributed to an increase in interference from micro sites due to the larger transmit power. Therefore, a micro site transmit power computed for a 100 m cell radius will be used in the following subsection.

4) Achieving a target capacity with optimal network deployment strategy: Our results from the previous subsections show that the network deployment strategy with 5 micro sites per cell gives the best performance. In this subsection we find the network strategy that satisfies *at least* a certain target system capacity per unit area (specifically, 30 Mbits/s/km^2) with minimum area power consumption.

As shown in Figure 6, a network with 5 micro sites per cell, macro inter site distance $D = 1200$ m and a micro site transmit power for a cell of radius 100 m has a system capacity per unit area equal to 31.23 Mbits/s/km^2 computed for optimal T when α and β are set to 1. Therefore, we expect the inter site distance of the network that

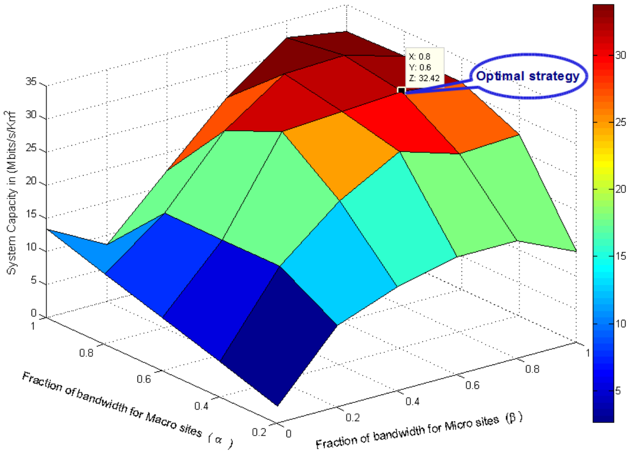

Fig. 7. Capacity per unit area of a network with $D = 1200$ m computed for optimal T and for different α and β values.

satisfies a minimum of 30 Mbits/s/km^2 to be close to 1200m.

We perform a brute force search for α, β and T values for macro inter site distances of 1100 m, 1200 m, 1300 m. We found that for inter site distance $D = 1200$ m $\alpha = 0.6$ and $\beta = 0.8$ and $T = 0.3$ give us a system capacity per unit area of 32.42 Mbits/s/km^2 and an area power consumption $\mathcal{P} = 517.04$ watt/km^2. This is the best strategy we could get to satisfy our objective stated above.

Figure 7 shows the variation in system capacity per unit area as a function of $\alpha \in [0.2, 1]$ and $\beta \in [0, 1]$. As can be seen from the figure, the optimal values of $\alpha = 0.6$ and $\beta = 0.8$ for our objective are not the values that give us the best system capacity per unit area. Rather they are the values that satisfy the minimal capacity requirement with least energy consumption.

Figure 5 shows a cellular network of only macro base stations can achieve a system capacity per unit area of 30 Mbits/s/km^2 when the macro inter site distance $D \simeq 800$ m. From Figure 4, we can see the area power consumption of a network of only macro base stations with $D \simeq 800$ m is $\mathcal{P} \simeq 968.5$ 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.

VIII. 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. Applying a more robust bandwidth allocation scheme along with base station cooperation for interference mitigation may further improve our findings.

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