Step-Wise Optimal Low Power Node Deployment in LTE Heterogeneous Networks

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Abstract— **In this paper, we propose a step-wise optimal low power node (LPN) deployment algorithm for LTE heterogeneous networks. Our proposed LPN deployment algorithm takes signal quality, relative loading among macro cells and LPN cells, and user density into account. Simulation results show that the proposed algorithm can achieve close to 100% coverage gain and more than 50% average cell throughput gain over a random LPN deployment scheme.**

Keywords- Low power node, deployment, optimization

I. INTRODUCTION

As traffic demands and the number of subscribers continue to grow, conventional wireless cellular networks will not be able to support an increased number of users and meet their quality-of-service (QoS) requirements [1]. Recently, the notion of deploying low power nodes (LPNs) in the existing macro-cellular system has been attracting a plethora of attention from both academia and industry. In such a heterogeneous wireless network (HetNet), LPNs occupy the same amount of bandwidth as their macro counterparts. The key benefits of deploying LPNs and hence HetNets are three-fold: 1) effective traffic offloading; 2) cell capacity increase due to cell splitting gain (i.e., frequency reuse); 3) cell coverage increase as cell edge users can now be served by relatively resource-rich LPNs. However, the success of HetNets is highly contingent upon the effectiveness of LPN deployment, meaning that an effective and efficient LPN deployment strategy is crucial.

In the past few decades, the focus of deploying macro base stations is to enhance coverage performance [2]; therefore, most of the efforts in network planning were spent on identifying coverage holes (e.g., locations of poor geometries) and new base stations are dropped so as to boost the coverage performance. LPN deployment, on the other hand, focuses not only on coverage enhancement, but also on capacity improvement. Below are the key factors in determining the desirable locations of LPNs:

- *Interference caused by macro base stations (BSs) to pico UEs (i.e., pico UEs are users served by LPNs)* – this source of interference greatly affects the performance of pico UEs, since the transmit power of macro BSs is much higher than that of LPNs (e.g., 46dBm for macro BSs versus 30dBm for LPNs [3]). Thus, LPNs should be deployed in a location where the macro BS-to-pico UE interference is less severe.
- *Interference caused by LPNs to macro UEs (i.e., macro UEs are users served by macro BSs}* – the impact of this source of interference is relatively less compared to traditional macro BS-to-macro UE interference, since the transmit power of LPNs is usually low.
- *UE association* – resource allocation depends on how users are associated with macro BSs or LPNs. In generally, the more the users that are served by an access node, the less resources the users will receive, and hence the lower the throughput. Given a fixed range extension bias, an LPN should be placed at the location such that more UEs previously served by macro BSs can now be served by LPNs.
- *Geometry of existing macro UEs* – from the logs of the geometry of existing macro UEs in the macro-only cellular system, we can identify the coverage holes. LPNs can be deployed in those locations to improve coverage performance.
- *UE density* – this is an important factor in determining the effectiveness of LPNs. By identifying the areas where a UE density is high, LPNs can be deployed in those hotspots where the maximum number of users can be offloaded from macro BSs to LPNs. By balancing the loading between macro BSs and LPNs, spectral efficiencies and hence system capacity will improve.

In this paper, we propose a framework and step-wise optimal algorithm for LPN deployment in the existing macro-only cellular networks, taking all the aforementioned deployment factors into account. Our proposed deployment algorithm is to deploy LPNs one at a time and locates the best position for each LPN. Simulation results show that our proposed algorithm outperforms a cluster-center deployment approach and an edge-planned deployment approach, both of which are suggested by the 3GPP standards [3]. Notice that LPNs generally refer to both relays and picos. In this work, we only consider picos, although the framework can easily be extended to cover relay deployment

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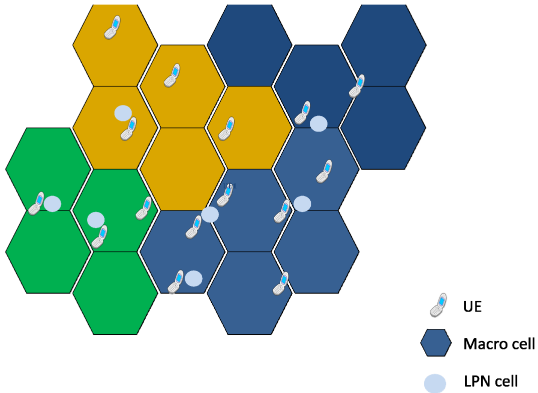


Figure 1 System model showing a typical HetNet system

II. System Model

The system model consists of existing macro BSs organized in a typical cellular layout and N LPNs to be deployed, depicted in Figure 1. The entire network is divided into a number of bins, where we assume there is 1 UE located at the center of each bin in the case of uniform UE distribution for the sake of simplicity. To model a hotspot where its UE density is w times higher than other areas, we assume there are w (>1) UEs located at the center of each bin which falls into a hotspot. Further, an LPN is to be dropped at the center of each bin.

We consider saturated traffic (i.e., full buffer traffic) and no user mobility in the system. For the sake of notional convenience, we consider that the network is a one-dimensional network in our problem formulation, but the extension to a realistic two-dimensional network is to be discussed in our solution approach.

III. Optimization Problem Formulation

A. *Constraints*

1) *Before dropping LPNs*

Consider the one-dimensional network with K possible LPN locations (i.e., bin centers) along a straight line. In the macro-only cellular network, the geometry of UE j (at location j) if served by BS m is given by

$$\gamma_j^{(m)} = \frac{P_m g_{L_M(m)j}}{\sum_{k\neq m} P_k g_{L_M(k)j} + \sigma}, \qquad j = \{1,2,\dots,K\} \tag{1}$$

where P_m is the transmit power of BS m, g_{ij} is the channel gain from BS at location i to UE j (at location j), σ is the thermal noise power, and $L_M(k)$ is the location of macro BS k in the system. In most of the wireless standards, the serving BS of a UE can be determined based on the strongest macro BS-to-UE link, as follows:

$$m^* = \arg\max_{\mathrm{m}}\left\{\gamma_j^{(m)}\right\} \tag{2}$$

According to our extensive internal simulation studies, the throughput of UE j can be estimated as follows:

$$r_j = \rho_m f\left(\gamma_j^{(m^*)}\right) \tag{3}$$

where r_j is the estimated throughput of UE j, ρ_m is the loading factor for macro BSs, and $f(\cdot)$ is a mapping function from geometries to throughputs. In macro-only cellular systems, where the user density in each cell is more or less the same, it is safe to assume that ρ_m is the same for all m.

2) *After dropping LPNs*

Suppose we are to drop N LPNs in the existing macro-only cellular system. The geometry of UE j if served by macro BS m is given by

$$\widehat{\gamma_j^{(m)}}(\mathrm{A}) = \frac{P_m g_{L_M(m)j}}{\sum_{k\neq m} P_k g_{L_M(k)j} + \sum_{\forall n}\sum_{\forall k} P_n g_{L_P(n)j} + \sigma} \tag{4}$$

where $L_P(n) = \arg max\,_i\{a_{kn} | \sum_{\forall k} a_{kn} = 1\}$, $l \in \{1,2,\dots,N\}$ (referring to LPN l), $m \in \{1,2,\dots,K\}$ (referring to macro BS m), and $\mathbf{A} = [a_{kn}]_{\boldsymbol{KxN}} = \begin{bmatrix} a_{11} & \cdots & a_{1N} \\ \vdots & \ddots & \vdots \\ a_{K1} & \cdots & a_{KN} \end{bmatrix}$, with a_{kn} being an assignment indicator, i.e., $a_{kn} \in \{0,1\}, \forall_{k,n}$. If LPN n is dropped at location k, $a_{kn} = 1$, or 0 otherwise. Since each LPN can at most be dropped once, we have the following constraint: $\sum_{k=1}^{K} a_{kn} \leq 1, \forall_n$. Assuming we have N LPNs to be dropped, we have the following constraint: $\sum_{n=1}^{N}\sum_{k=1}^{K} a_{kn} \leq N$. The geometry of UE j if served by LPN n is given by

$$\widehat{\gamma_j^{(n)}}(\mathrm{A}) = \frac{(\sum_{k=1}^{K} a_{kl}) P_l g_{L_M(l)j}}{\sum_{\forall k} P_k g_{L_M(k)j} + \sum_{n\neq l}\sum_{\forall k} P_n g_{L_P(n)j} + \sigma} \tag{5}$$

Assuming a fixed range extension (RE) in favor of LPNs, the serving cell of UE j can be determined by

$$q^* = \arg\max_{\mathrm{q}}\left\{\begin{array}{ll} \widehat{\gamma_j^{(q)}}(\mathrm{A}), & where\ q \in macro\ BS \\ \beta\widehat{\gamma_j^{(q)}}(\mathrm{A}), & where\ q \in LPN \end{array}\right\} \tag{6}$$

where $\beta = 10^{\left(\frac{RE}{10}\right)}$ with RE being the range extension in dB. Thus, the throughput of UE j can be approximated by

$$\widehat{r_j}(\mathrm{A}) = \begin{cases} \rho_m f\left(\widehat{\gamma_j^{(q^*)}}(\mathrm{A})\right), where\ q^* \in macro\ BS \\ \rho_p f\left(\widehat{\gamma_j^{(q^*)}}(\mathrm{A})\right), \quad where\ q^* \in LPN \end{cases}$$

where ρ_p is the loading factor for LPNs. In general, $\rho_{p>}\rho_m$, since there are typically more UEs served by a macro BS than an LPN.

B. *Problem formulation*

To make our model generic, we employ the notion of utility functions, where the objective function can be formulated as follows: $\max\{\sum_{\mathrm{k=1}}^{\mathrm{K}} \mathrm{U_k(A)}\}$, where $\mathrm{U_k(A)}$ is the utility of UE k. In this work, we consider the well-known sum-log-throughput maximization: $\mathrm{U_k(A) = w_k \log\left(\frac{\hat{r}_k(A)}{r_k}\right)}$, where $\mathrm{w_k}$ is the relative user density at location k compared to uniform user distribution. Therefore, our LPN deployment optimization can be formulated as follows:

$$\max\left\{\sum_{\mathrm{k=1}}^{\mathrm{K}} \mathrm{U_k(A)}\right\}$$

subject to

$$a_{kn} \in \{0,1\}, \forall_{k,n} \sum_{k=1}^{K} a_{kn} \leq 1, \forall_n \sum_{n=1}^{N}\sum_{k=1}^{K} a_{kn} \leq N$$

This OP contains a non-convex non-concave non-continuous objective function, which is generally difficult to solve [4]. We propose a step-wise optimal greedy approach to solve this OP. Notice that, to extend this mathematical formulation to a two-dimensional network, we simply expand the search space from $\{j\}$ to $\{x, y\}$.

IV. PROPOSED APPROACH

The methodology of our proposed approach to solve the LPN deployment problem can be briefly summarized as follows:

1. For each LPN *n*, we evaluate the utility of each UE when LPN *n* is dropped at location *j*.
2. Find the location such that the sum utilities of all the UEs are maximized, and set $a_{kn} = 1$.
3. Repeat Steps 1-2.

Since we find the best location of each LPN candidate over the entire search space, this algorithm is step-wise optimal. Below is the holistic solution approach to LPN deployment over the 2-dimension space with practical considerations:

1. Divide the entire area into several bins (e.g., 250 x 250 number of bins), where the distance between the centers of two adjacent bins is ISD (i.e., inter-site distance) divided by the number of bins per dimension. For example, if the number of bins per dimension is 50, the separation distance between the centers of two adjacent bins is 10m for ISD=500m (or 35m for ISD=1732m).
2. For each bin, we consider a "dummy UE" at the bin center (*i,j*), record its serving macro BS, and compute its throughput, denoted by $r(\mathrm{i,j})$.
3. For each possible LPN location (*i,j*), compute the utility of each dummy UE in the *LxL* box with (*i,j*) being the center, where L should be large enough to cover the area of interest: compute its new throughput as if an LPN is dropped at (*i,j*).
    a. Assuming cell selection based on a fixed bias scheme - If the LPN RSRP is greater than the macro RSRP minus a fixed bias, the dummy UE of interest will associate with this LPN: update its serving BS, its geometry and its effective throughput, where the effective throughput is given by

    $$\hat{r}(i,j) = \rho_p r(\mathrm{i,j})$$

    where ρ_p is the relative loading in an LPN cell with respect to that in a macro cell. Here, we approximate ρ_p by the ratio of the number of macro UEs and the number of LPN UEs. Given a fixed number of UEs/macro cell, the more the macro UEs, the less the LPN UEs, the more the resources that can be allocated to LPN UEs and hence the larger the value of ρ_p.

    b. If the LPN RSRP is less than the macro RSRP minus a fixed bias, the dummy UE of interest still remains associated to its serving macro BS, but the geometry needs to be updated by considering the interference generated by the LPN, and a new throughput, $\hat{r}(i,j)$, is computed.

    c. Calculate the utility at (*i,j*) by combining its effective throughput and its weight based on the user density at (*i,j*) as follows: $U(\mathrm{i,j}) = \mathrm{w}(\mathrm{i,j}) \times \log\left(\frac{\hat{r}(i,j)}{r(\mathrm{i,j})}\right)$, where $\mathrm{w}(i,j)$ is the relative user density at location (*i,j*) compared to uniform user distribution.

    d. Calculate the effective utility at (*x,y*): $U^{eff}(\mathrm{x,y}) = \sum_{(\mathrm{i,j})\in\mathrm{Cov(x,y)}} U(\mathrm{i,j})$, where *Cov(x,y)* is the area of interest with respect to (*x,y*), i.e., *LxL* box with (*x,y*) being the center. If the complexity is not a concern, *Cov(x,y)* can be as large as the entire network.
4. Drop each LPN at (x^*, y^*) such that $(\mathrm{x}^*, \mathrm{y}^*) = \arg\max\{U^{eff}(\mathrm{x,y})\}$ is maximized, i.e. choose the point that has the largest utility and drop the LPN there.
5. Update the throughput of each (*i,j*) in the *LxL* box with $(\mathrm{x}^*, \mathrm{y}^*)$ following Steps 3a-3b; replace $r(\mathrm{i,j})$ by $\hat{r}(i,j)$
6. Repeat Steps 3-5 until all LPNs are dropped or a stopping condition is reached.

V. SIMULATION RESULTS

We conduct system-level simulations to illustrate the merits of the proposed step-wise optimal LPN deployment algorithm. We consider a network with 19 macro sites with 3 sectors per site. We follow most of the standard Long Term Evolution (LTE) simulation assumptions specified in 3GPP TR 36.814 [3]. The specific assumptions related to our simulation setup are shown in the following table:

Table 1 Simulation assumptions

Parameters	Value
ISD	500
Cell association	Strongest link
Number of UEs per macro sector	60
Number of UE clusters per macro sector	5
Number of UEs per UE cluster	10

For performance comparison, we consider the following control algorithms:

- *Random deployment* – LPNs are randomly deployed. This approach serves as a baseline approach.
- *Edge-planned deployment* – LPNs are deployed near the cell edge of a macro sector to deal with the coverage holes. In other words, LPNs are placed at the locations with the lowest geometries without considering shadow fading. In practice, the long term geometry of a UE can be approximated by considering its path-loss only.
- *Farthest cluster-center deployment* – Given a number of UE clusters per macro cell, an LPN is placed at the center of the cluster which is the farthest from its macro BS. Should the number of LPNs be larger than the number of

clusters, the remaining LPNs are randomly dropped. Assuming the hotspot locations are known, the distance between a UE cluster center and its macro BS can be obtained.

Performance comparison in terms of coverage (i.e., 5%-tile throughput) and average cell sum throughput is depicted in Figure 2. Clearly, the edge-planned deployment, the farthest cluster-center deployment and the proposed deployment give better performance than the random deployment. It can also be observed that farthest cluster-center deployment outperforms edge-planned deployment. This observation also holds for 8 UEs/cluster. In other words, when the user density in a cluster is high, placing an LPN at a cluster center is better than at the location with the lowest geometry in terms of both coverage and sum throughput.

By considering the user density, loading, and signal quality of each point in the network topology, the proposed approach achieves the best system performance. For 5 picos per macro cell, the performance gains can be up to 98% in coverage performance and 55% in average cell sum throughput performance compared to the random deployment, which are an additional 28% gain in coverage and 34% gain in average cell sum throughput on top of farthest cluster center deployment. The proposed algorithm also outperforms its counterparts regardless of the number of picos dropped per macro cell.

VI. DISCUSSIONS

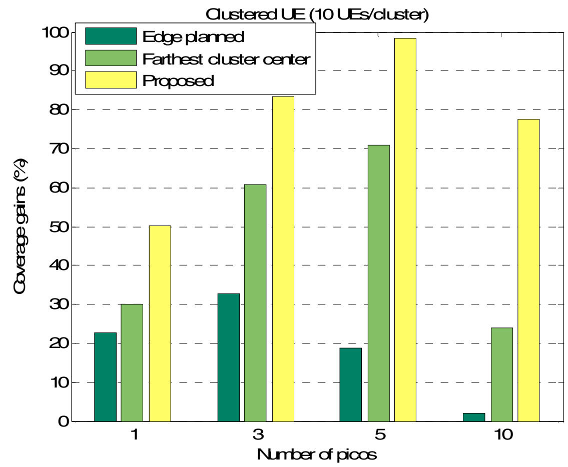
In the current proposed LPN deployment algorithm, we assume the following information available:

a. Pathloss between macro BSs and each UE
b. Shadow fading between macro BSs and each UE
c. Pathloss between LPNs and each UE
d. Shadow fading between LPNs and each UE
e. User density

In practice, a), and b) should easily be available. For c), we need to calculate the distance between an LPN and a UE, while d) needs more effort to obtain the information of shadow fading. For e), traffic monitoring is required, but it could be conducted fairly easily, e.g., a metropolitan area (e.g., shopping mall) will have higher user density than a remote area. Realistically, we might not be able to gather all of the above information. For example, if the knowledge of shadow fading between LPNs and each UE is not available, we can ignore their shadow fading. Or, if the user density is not known, we can assume uniform UE distribution. Further work is needed to evaluate the performance with imperfect knowledge of a) to e).

VII. CONLCUSIONS

We proposed a step-wise optimal low power node (LPN) deployment algorithm for LTE heterogeneous networks, taking RSRPs, relative loading in macro and pico cells, and user density into consideration. Simulation results showed that the proposed LPN deployment approach outperforms a random deployment scheme, edge-planned deployment scheme, and clustered-center deployment scheme. Discussions on practical implementation of the proposed algorithm are presented. Further work includes lower-complexity LPN deployment algorithm design.



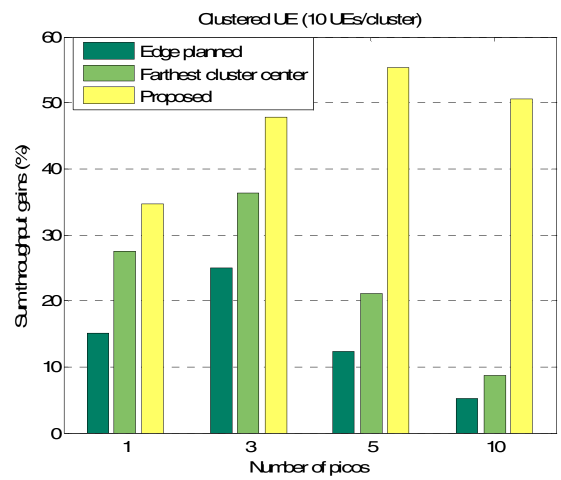


Figure 2 Performance gains are illustrated below (where the random deployment is served a baseline)

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