Towards a Framework for Small-cell Network Planning

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Abstract— To address the exponential growth of traffic on mobile cellular networks, heterogeneous networks have been proposed in which numerous small-radius microcells commonly referred to as "small cells" are placed alongside traditional macrocells. The practical rollout of these small cells is challenging. For example, the effects of land terrain and urban geography on cellular mobile signal propagations can significantly influence transmission quality and coverage. In this paper, we describe a small-cell planning framework that takes into consideration the effects of land terrain variation and urban geography in planning the location of the small cells. Our framework is shown to utilize fewer cells than the maximum limit of 30 cell sites/km^2 in urban area for LTE 1800 MHz network. We further formulate a Linear Program to obtain the optimal operating power of these small cells whilst constrained by the power and capacity requirements and subjected to daily capacity demand variations. Our preliminary results show that with our small cell power management scheme which is based on traffic and capacity demand, tangible power savings can be achieved throughout the day.

1. INTRODUCTION

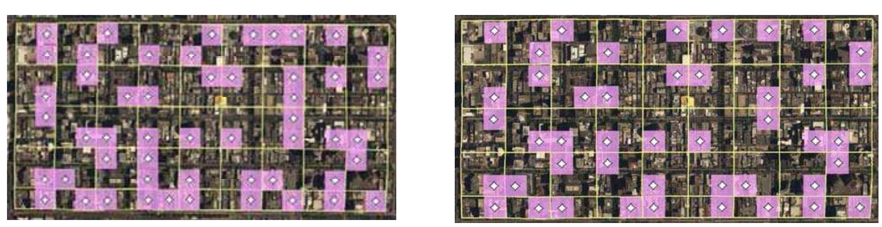
The recent surge in smartphone and mobile tablet usage has placed tremendous strain on mobile bandwidth. To address this exponential growth, heterogeneous networks have been recently proposed with optical fiber technology as the backhaul solution, thereby allowing untethered bandwidth to the mobile infrastructure. In a heterogeneous network, numerous small-radius microcells commonly referred to as "small cells" (SCs), are placed alongside traditional macrocells [1]. A small cell Base Station (BS) has a much smaller coverage radius range than that of a traditional macrocell, typically at 50 m to 300 m. It is designed to achieve a small footprint with features such as low-cost and low power, and is to be deployed in a plug-and-play fashion that requires minimal regular maintenance. However, the practical rollout of small cells is not without its challenges. As discussed in the abstract, the effects of land terrain and urban geography on cellular mobile RF signal propagations significantly influence transmission quality and coverage. Varying geographical terrain posing obstructions for direct line-of-sight signal path between the transmitting BS and receiving mobile station, initiates significant signal loss and causes Non line-of-sight propagation. Further, street orientation and building blocks especially in urban areas, cause signal reflections which in turn, lead to significantly weakened signal reception for cell areas with smaller radius. The BS antenna height also influences cell positioning by affecting coverage. Thereby, appropriate cell location planning for placing small cell sites with optimal antenna height especially in urban areas, is essential. Recent studies have also shown that the BSs of cellular networks collectively contribute to ∼60% of the total energy consumption [2]. Hence, considering the potentially high BS density in small-cell networks, it is imperative that rigorous studies be undertaken on energy efficient power control mechanisms which account for the radiating power and required capacity enhancements that SCs can offer.

In this paper, we review a preliminary small-cell planning framework which we have recently proposed which accounts for the effects of land terrain variation and urban geography in selecting the most appropriate locations for small cells in an urban area. For illustration purposes, we chose a part of the Melbourne Central Business District (CBD) urban area for cell planning [3]. In our proposed framework, the relatively higher geographic elevations are first selected as potential locations for a small cell deployment. A common radius for all cell sites is then chosen within the typical urban area small cell radius range. For the selected cell radius, the signal strength and coverage ability for each cell site is then tested taking into account an antenna height of just below average building height. Finally, redundant cell locations are discarded from the initial planning to satisfy the maximum limit of cell sites per km^2 urban area. Our framework is shown to utilize fewer cells than the maximum limit of 30 cell sites/km^2 in urban area for LTE 1800 MHz network [4]. A similar cell planning framework was proposed in [5], however the authors only considered terrain characteristics and discounted urban geography effect for macrocell rather than small cell deployment. Further, we present a Linear Program (LP) to obtain the optimal operating power of SCs whilst constrained by the power and capacity requirements and subjected to daily capacity demand variations [5]. The formulation of the LP and the datasets and model parameters used in our evaluations are presented here in this paper. Even though some related studies in this area have studied energy efficiency of small-cell networks via several network models, to the best of our knowledge, a deduction to LP for the problem at hand is performed for the first time by our team.

2. TERRAIN BASED SMALL CELL PLANNING FRAMEWORK: DESCRIPTION AND EVALUATION

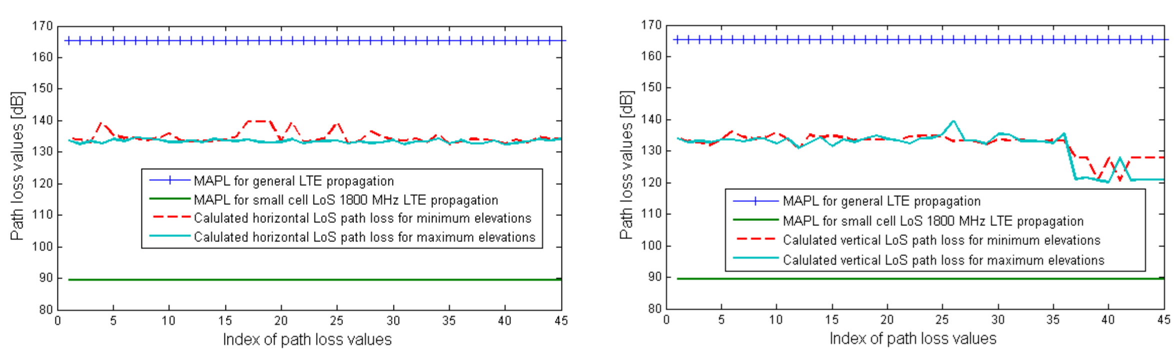
There are four critical steps to our proposed small-cell planning framework: (a) selecting potential small-cell site locations; (b) allocating a proper cell radius value for each cell area; (c) testing coverage and signal strength levels for all cell areas with the fixed cell area; and (d) finalizing appropriate cell locations. As discussed, a test section of the Melbourne CBD of 900 m × 1800 m was chosen for our cell planning. Geographic terrain elevation information was extracted using Google Earth software. In order to select appropriate small cell locations, the case study area was divided into a two-dimensional (2D) rectangular terrain grid of multiple same-sized unit squares, having 100 m sides. The elevation value for each unit square area measured horizontally across the grid from left to right in each row, was obtained and stored in the corresponding cell of a terrain grid matrix having 9 rows and 18 columns. In this reported work, we arbitrarily chose a 200 m radius for each cell site, corresponding to the typical small-cell area range. To reflect this small cell area range in our cell planning, four square cells, starting from the first cell on top left, were grouped together to form one intended coverage block square of 200 m side. The area with highest value among each four elevations of each coverage block was then obtained as the potential candidate cell site. This process was then repeated for all coverage blocks resulting in an initial 52 small-cell locations as illustrated in Figure 1(a), whereby the pink squares are the BS location boundaries within which the small-cell BS as white diamond shape is positioned.

To evaluate the feasibility of our framework, each small-cell location was tested for sufficient coverage through path losses accounting for both Line-of-Sight (LOS) and Non-Line-of-Sight (NLoS) scenarios for a BS antenna height of 9 m and MS antenna height of 1.5 m [6]. For LoS propagation without obstructions, the Hata path loss model as described by Nissirat et al. [7] for small urban city microcells, and with an added correction factor to consider geographic terrain slope effects, was applied. In the NLoS case, a diffraction building loss of 23.73 dB accounting of for antennas just



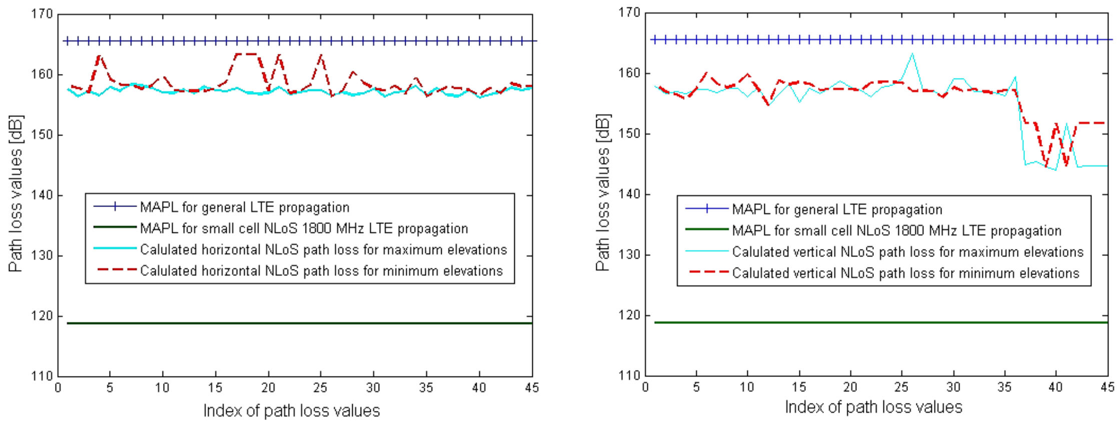
(a) (b)

Figure 1: (a) Initial planning of 45 coverage blocks with 52 potential small cell site locations across Melbourne CBD. (b) Final selection of 45 small-cell site locations across the Melbourne CBD.



(a) (b)

Figure 2: (a) Horizontal LoS path loss profile. (b) Vertical LoS path loss profile.



(a) (b)

Figure 3: (a) Horizontal NLoS path loss profile. (b) Vertical NLoS path loss profile.

below rooftops [8], was added to the computed LoS path loss. For both LoS and NLoS situations, we measured the signal paths within our constructed 2D terrain grid from the farthest side of each cell location boundary (pink square) towards its cell area edges (yellow line). The corresponding path losses for the minimum elevation in each cell coverage area was similarly computed and compared to those of maximum elevations. The LoS signal loss profile when measured horizontally and vertically in the terrain grid are shown in Figures 2(a) and 2(b), respectively. Results in Figure 2(a) show that our calculated LoS propagation losses for maximum terrain elevations, remain lower in most cases and almost equal in others, to those of the minimum elevations. For Figure 2(b), in only a few cases, the maximum elevation losses are relatively higher than minimum elevation losses. Both calculated losses are also under LTE MAPL value of 165.5 dB [4].

Figures 3(a) and 3(b) illustrate the NLoS signal loss profiles of horizontal and vertical paths for the terrain grid, respectively. Results in Figure 3(a) show that LoS losses are lower for most maximum height locations, than those of the corresponding minimum ones, while almost the same for both in other occasions. Results in Figure 3(b) displays higher NLoS losses for most minimum elevations, except for a few occurrences. These NLoS losses are also below LTE MAPL. Finally, redundant site locations with the same maximum height from each coverage block are discarded from the initial planning. Here, only the highest elevation point with least path loss within each coverage block is retained, decreasing the number of final cell sites from 52 to 45 as shown in Figure 1(b), thus meeting the maximum cell site limit of 49 cells for the 1.62 km^2 area we studied.

3. CONTROL OF TRANSMIT POWER IN SMALL CELLS — OPTIMIZATION PROBLEM AND EVALUATION

As discussed in Section 1, recent studies have highlighted the high energy consumption of BSs, amounting to ∼60% of the total energy consumption in cellular networks [2]. Care must be taken in the operation of small cell networks even though each small cell benefits from low operating powers. The main reason is that high density deployment can be expected in small cell networks since each small cell has only a small coverage area of 50 to 300 m. The collective power consumption of the network may therefore be significant. Here, a Linear Program (LP) which was formulated to optimize the transmit power of the small cells based on hourly network capacity demand of a mobile access network, is presented [8]. Our focus is on three distinct geographical areas; urban, suburban, and rural based on population density. Transmit powers of a base station is derived considering the capacity requirement of the users served. The LP is solved to optimally control the transmit power of SCs to evaluate the benefits of demand based power optimization.

Firstly, we focus on a segment of the wireless access network which includes a macro basestation and multiple randomly distributed small cell base stations. Note that in the LP, only transmit powers of base stations disregarding any other power consuming components, are optimized. Let N be the set of SCs in the network segment. Then, the objective function can be expressed as;

$$\text{minimize } P_{MC} + \sum_{i \in N} P_i \tag{1}$$

where P_{MC} is the power of the macro basestation and P_i represents the power of the ith SC basestation. Then, a capacity constraint is enforced to ensure that all users connected to a SC receive required capacity, and a power constraint is enforced to represent physical equipment limitations. Let M_i be the set of users connected to the ith SC, then the capacity constraint can be shown as:

$$\sum_{m \in M_i} C_{m,i} \geq n_i C_{th} \; \forall \; i \in N \tag{2}$$

where $C_{m,i}$ denotes the capacity from the ith small cell to the mth user, C_{th} denotes the capacity demand threshold per user and n_i denotes the number of users connected to the ith SC. All users connected to the SC receive the threshold capacity. This capacity constraint is then reconstructed into a power constraint using Shannon's formulae. The resulting constraint is as follows:

$$P_i \geq 2^{\left[\frac{C_{th}}{B} - \frac{1}{N_i} \log_2 \left(\frac{\prod_{m \in M_i} G_{i,m}}{\prod_{m \in M_i} \left(\sum_{j \in N, j \neq i} P_{avg} G_{j,m} + \sigma^2 \right)} \right) \right]} \; \forall \; i \in N \tag{3}$$

In (3), N_i is the number of users connected to the ith SC base station. $G_{i,m}$ is the slow fading gain between the mth user and ith SC. P_{avg} is the average transmit power of a SC whilst σ^2 represents the interference noise power. Note that the revised constraint will now also enforce a lower bound on the transmit powers. Further, the transmit power of the SC antenna is bounded by a maximum threshold due to physical equipment limitations. This is considered as the power constraint in our formulation. The power constraint is given by:

$$P_i \leq P_{sc,\max} \; \forall \; i \in N \tag{4}$$

where $P_{sc,\max}$ is the maximum allowable transmit power of a SC. We consider the microcell base station to operate at a constant power level of $P_{mc,\max}$. The slow fading gain in constraint (3) is modeled as in [9] where:

$$G_{i,m} = K_0 \times \; 10^{\frac{\beta_{i,m}}{10}} \times d_{i,m}^{-\eta} \tag{5}$$

The parameter K_0 is a factor accounting for the effects of antenna gain and carrier frequency, $\beta_{i,m}$ is a Gaussian random variable with zero mean and standard deviation of 4 dB to account for log-normal shadowing effects, $d_{i,m}$ is the distance between mth user and ith SC, and η is the path loss exponent. Hourly capacity demand statistics are derived from a study that estimated network load of a mobile access network of a mobile operator [8]. Other parameters considered in this work are listed in Table 1.

Figure 4(a) shows the total transmit power of small cells against the hourly capacity demand variations throughout the day. A network segment with 50 small cell base stations was considered. Results indicate peak transmit power corresponding to the peak capacity demand at 1600 hrs. Among the three scenarios, urban and suburban environments indicate increased transmit power compared to the rural environment, due to more users being served by the small cells. The dotted horizontal lines indicate the peak transmit power in each scenario. This power level is considered as a baseline where the small cells operate continuously. We then evaluated the the small cell network with respect to this baseline in Figure 4(b). The power savings are averaged over the three population density cases. Results show maximum savings during low traffic periods and minimum

Table 1: Parameters considered in the model.

Parameters	**Values**
Area	1 km × 1 km
Bandwidth (B)	1.5×10^6 Hz
K_0	10^3
Path loss exponent (η) [6]	4 (urban) 3 (sub-urban), 2 (rural)
Population density [7] (inhabitants per km^2)	> 400 (urban), 150 to 400 (suburban), < 150 (rural)
σ^2	10^{-10} W
$P_{sc,\max}$, $P_{mc,\max}$ [8]	6.3 W, 80 W
$P_{sc,avg}$	5 W

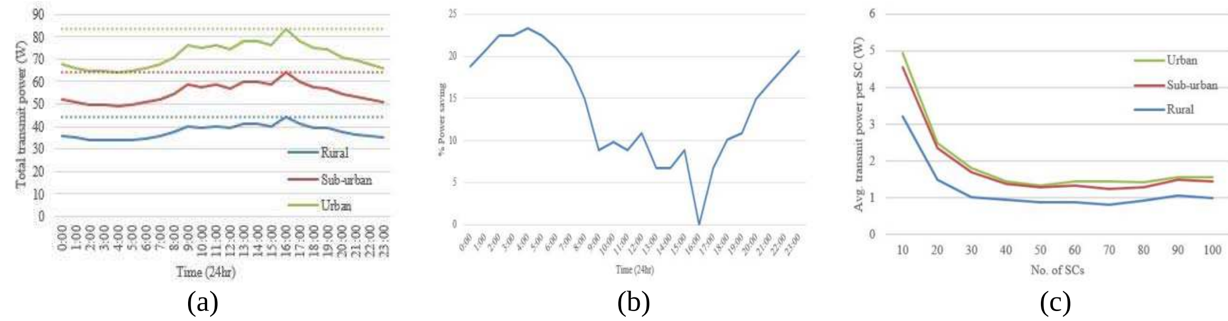


Figure 4: (a) Total transmit power under varying capacity demand throughout the day; (b) Percentage of transmit power savings, and (c) Average transmit power per SC as a function of number of SCs..

savings the peak traffic hour. Figure 4(c) presents the average transmit power per small cell as a function of number of small cells deployed at the peak traffic hour. Results show that as the number of small cells increases, the average transmit power decreases due to users being shared amongst more small cell and the increased freedom to choose a small cell with higher signal strength. We observe that the average transmit power tends to saturate when the number of small cell increases. This suggests that over-densification of small cells beyond certain a deployment number does not improve power savings though bandwidth capacity per user is increased. Further, we observe that the increase in population density will increase transmit powers. However, as population density is increased, the average power per small cell becomes less dependent on this parameter, as observed by the small difference between the urban and suburban result curves.

4. SUMMARY

In this paper, we described a small-cell planning framework that takes into consideration the effects of land terrain variation and urban geography in planning the location of the small cells. Our framework is shown to utilize fewer cells than the maximum limit of 30 cell sites/km^2 in urban area for LTE 1800 MHz network. Additionally, a Linear Program proposed to obtain the optimal operating power of small cells whilst constrained by the power and capacity requirements and subjected to daily capacity demand variations, was presented. The model was evaluated under urban, sub-urban and rural enviroments, showing tangible power savings throughout the day as compared to fully powered small cells.

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