Cost and Feasibility Analysis of Self-deployed Cellular Network

Du Ho Kang, Ki Won Sung, and Jens Zander
Wireless@KTH, Royal Institute of Technology (KTH)
Electrum 229, 164 40 Kista, Sweden
Email: {dhkang, sungkw, jenz}@kth.se

***Abstract*—A self-deployed network is considered to be one of cost-efficient deployment solutions by skipping an expensive network planning process. However, it may result in the serious degradation of capacity or the infeasibility of coverage constraint due to the rise of interference although radio adaptation techniques are employed. Therefore, deployment decision makers, e.g., operators, need to identify when and where the self-deployed network is feasible and economical compared with the planned network. For this, we estimate the average network throughput of the self-deployed network subject to a coverage constraint and compare it with the planned network. Three distinct regions of self-deployment are identified where different deployment strategies are required: infeasible, cost-effective, and uneconomical. We evaluate how the regions alter according to different channel environments and make suggestions for economical deployment.**

I. INTRODUCTION

As a gap between capacity in wireless cellular networks and the revenue of operators increases due to soaring traffic demand with flat pricing schemes, cost-saving deployment strategies become more and more essential. While equipment cost turns cheaper due to equipment vendor's competition and technology evolution, site-related cost relatively remains dominant in total deployment cost [1]. One of major cost-driving factors in the site-related cost is planning the locations of base stations (BSs) which requires expensive engineering efforts. For reducing the planning cost, the concept of a self-deployed network is recently of great interest and has actively been studied [2], [3].

Unlike conventionally planned networks, BSs in the self-deployed networks are not carefully deployed by engineers or sometimes randomly placed by unskillful end-users. Consequently, self-deployed BSs may be inefficiently deployed such that they cannot offer the minimum required rate to some users owing to coverage gap or excessive interference from cell overlap. This requires installing more BSs to fill the coverage gap in some areas. It also needs to turn off some BSs to reduce the excess interference in other areas. In a nutshell, the saving of the planning cost leads to extra equipment cost in the self-deployment. In some cases, the unplanned BS locations may not fulfill the capacity or coverage requirement even with intercell interference mitigation/avoidance schemes. Thus, deployment decision makers, e.g., operators, should investigate whether the self-deployed networks can provide the minimum required rate in the service area, i.e., coverage. Then, they need to explore if the self-deployed network is more economical than the planned network in terms of the total deployment cost.

Most of existing studies on the self-deployed networks focused on technical aspects such as capacity or coverage analysis, optimal interference mitigation and avoidance schemes, and network architecture designs [2], [3]. In contrast, relatively few studies have been done in the economic perspective [4], [5]. In [4], a cost comparison between self-deployed networks and conventional networks is presented in a particular usage scenario by assuming constant capacity and coverage per BS. The author of [5] intensively analyzed the total deployment cost when the self-deployed network is mixed with different types of networks. However, as acknowledged in [6], both economic and technical aspects need to be considered together for the design of cellular networks. For the planned networks, a cost optimization problem was addressed that jointly considered various technical aspects such as transmit power and antenna heights [7], [8]. However, the techno-economically integrated analysis has not been in place for the self-deployed network which requires a different cost structure and deployment model.

In this paper, we assess the cost of a self-deployed network with a throughput requirement subject to a coverage constraint. Particularly, we consider inter-cell interference mitigation/avoidance techniques in the analysis by employing transmit power control and frequency selection. This will bridge the gap between technological and economic studies on the self-deployment. We address the following question:

- Can the self-deployment satisfy the coverage constraint?

If this is the case, the second question is posed:

- Is the cost of self-deployment cheaper than the planned-deployment for a given throughput requirement?

In order to answer these, we first examine the average network throughput subject to the coverage constraint as a function of the number of deployed BSs. If the coverage is satisfied, we assess the total deployment cost of the self-deployed network and compare it with that of the planned network.

The main contributions of this paper are summarized as follows. Firstly, we identify under which performance requirements or environments the self-deployment stay economical than planned-deployment. Secondly, we investigate the sensitivity of the coverage constraint on the technical feasibility.

Thirdly, we explore how deployment decisions should be adjusted according to various shadowing and multichannel environments. The remainder of this paper is organized as follows: we describe a system model and a performance metric in Section II and III, respectively. Section IV presents a simulation model, and numerical results are given in Section V. Then, Section VI concludes this paper.

II. SYSTEM MODEL

We consider a finite service area set $\Omega \subseteq \mathbb{R}^2$. When N BS locations are given by a set $l \subseteq \Omega$, Ω is divided into several cells Ω_i occupied by BS $i \in \mathcal{B}$ which is defined as

$$\Omega_i := \{x | p_{r,i}(x) \geq p_{r,j}(x), x \in \Omega, \forall j \neq i\}, \tag{1}$$

where $p_{r,i}(x)$ is the received power at $x \in \Omega$ from BS i. Note that $p_{r,i}(x)$ is calculated by $g_i(x)p_i$ where $g_i(x)$ and p_i are a channel gain from BS i to location x and transmit power of BS i. When a user locates in $x \in \Omega_i$, signal to interference and noise ratio (SINR) can be obtained as,

$$\gamma_i(x) = \frac{p_{r,i}(x)}{\sum_{j \in \mathcal{B} \setminus i} \theta(f_i, f_j) p_{r,j}(x) + n_o}, \tag{2}$$

where n_o and $\theta(f_i, f_j)$ are noise power and an orthogonality function of operating frequencies f_i and f_j of BS i and j, respectively. $\theta(f_i, f_j)$ gives 1 when BS i and j operate in the same frequency channel and otherwise, 0. We also calculate a rate $r_i(x)$ from Shannon formula as

$$r_i(x) = \min(\log_2(1 + \gamma_i(x)), r_{max}) \text{ (bps/Hz)}, \tag{3}$$

where parameter r_{max} reflects the maximum sustainable rate in practice. When assuming that users are uniformly distributed in Ω, we define conditional expected network throughput λ_c for a given BS location set l as

$$\lambda_c := \sum\nolimits_{i \in \mathcal{B}} W_i E[r_i | l] \text{ (Mbps)}, \tag{4}$$

where W_i represents bandwidth (MHz) allocated in BS i. Let γ and γ_t be SINR of a user and its threshold for the minimum required rate. Then, users can experience outage when $\gamma \leq \gamma_t$ due to high co-channel interference or weak signal strength. Thus, the coverage for a given l can be described by conditional outage probability defined as

$$\nu_c := Pr[\gamma \leq \gamma_t | l]. \tag{5}$$

A. BS Deployment Strategy

According to how carefully BSs are placed, we differentiate two deployment strategies as follows.

1) Self-deployment: We assume that the self-deployed network is built by end-users with self-configurable BSs [3]. In order to make the end-users capable of deploying BSs, we assume that BSs are plug-and-play based small equipments which do not need dedicated installation space [3]. Since the end-users do not have any professional radio network planning knowledge and tools, they deploy several BSs without effort in a place where a wired backbone infrastructure is accessible. Typically, they sketch a network topology to ensure that BSs are quasi-uniformly distributed by visually inspecting pre-placed BSs or following some basic guidelines given in a technical manual. Thus, the case that BSs are co-located in the same position is unlikely to happen and is a too pessimistic scenario. Accordingly, we model that BSs are randomly placed with uniform distribution but with the minimum BS separation distance in a sequential manner.

2) Planned-deployment: In this case, all BSs are deployed at once in the optimal positions acquired by a location optimizing process based on costly channel measurements. Since channel measurements in Ω is not practical at all, we instead adopted a grid-installation approach for optimizing BS locations [9]. In this model, M and K equally-spaced points are pre-selected out of Ω for the candidate locations of N BSs and for measurement points, respectively (i.e., $N < M < K$). We formulate this into a general combinatorial problem selecting N BS locations out of M candidate locations. The objective of location planning aims at maximizing average signal qualities in the entire measuring points in a set $\mathcal{K}$, i.e., $\sum_{i \in \mathcal{K}} \log_2(1 + \text{SNR}_i)$. Note that SNR_i represents signal to noise ratio at measurement point i from BS offering the strongest signal quality when fixed transmit power is used.

B. Interference Mitigation and Avoidance

Most of cellular networks use advanced radio resource management schemes, e.g., link adaptation or dynamic channel allocation, to ensure the achievable performance for a given network topology. Therefore, it is necessary to consider interference mitigation/avoidance schemes regardless of the deployment strategies. In particular, we assume that a joint transmit power control and frequency channel selection is employed in the considered network. Once the BS location set l is determined by either planned-deployment or self-deployment, the transmit power vector **p** and the frequency vector **f** of BSs need to be adjusted for managing inter-cell interference. In practice, after BSs are configured to connect the central server via a infrastructure backbone, the central server gathers local measurement information from each BS in order to assign the best power-frequency profile to each BS. Since instantaneously updating **p** and **f** is impractical due to a time-varying channel and limited processing capability, we consider a long-term adaptation in order to compensate the irregular pattern of BS topology. Let us consider a cellular network which targets to maximize λ_c subject to $\nu_c < \delta$. Note that δ denotes the constant outage threshold. Then, for a given l, we formulate this problem as follows:

$$\begin{array}{ll} \text{maximize} & \lambda_c(\mathbf{p},\mathbf{f}) \\ \text{subject to} & 0 \leq p_i \leq p_{max},\ f_i \in \mathcal{F},\ \forall\ i \\ & \nu_c \leq \delta \end{array}$$

Note that $\mathcal{F} = \{1, ..., n_f\}$ represents a frequency set with n_f available frequency channels while p_i and p_{max} are referred to as the transmit power of BS i and the maximum transmit power, respectively.

III. PERFORMANCE METRIC

Since our objective is investigating technical feasibility and deployment cost, we consider not only a technical metric but also an economic metric.

A. Technical Measure

As we can have different realizations of BS location set l for a given N deployed BSs, we measure the outage probability which is defined as ν=Pr[$\gamma < \gamma_t$]. The coverage of N BSs is considered as *feasible* regardless of deployment costs if the network can provide $\nu \leq \delta$. Otherwise, we call N BSs *infeasible*. Likewise, in order to estimate the total deployment cost for given network throughput, we also measure the network throughput in an average sense for a given N BSs. For this, we simply obtain average network throughput $\lambda = E[\lambda_c]$ by averaging over different BS location realizations of l.

B. Economic Measure

Once we have λ for a given N deployed BSs, we can acquire the total deployment cost C_{tot} under the following cost structure. The total deployment cost of a general cellular network consists of radio equipment cost and site-related cost which are the linear function of N [10]. We presume that the radio equipment cost per BS is same regardless of the deployment strategies since same BS equipments and network architectures are used in both cases. Since we assume book sized BS equipments with plug-and-play functionalities, we can also save site-related cost requiring civil works. For instance, cost for antenna titling, site acquisition, and initial parameter configurations can be ignored. Nevertheless, the planned network apparently needs more effort for installation from the channel measurement and the location optimization process. Also, access to a backbone infrastructure may not be readily available at the installation place so that it requires additional wiring with extra costs. Accordingly, we assume that the site-related cost is essentially dominated by the planning cost which includes the location optimization and wiring cost. From this, we simplify the total deployment cost as

$$C_{tot} := N(C_r + C_p), \tag{6}$$

where C_r and C_p are the radio equipment cost per BS and the planning cost per BS, respectively. Note that the self-deployed network has C_p=0 since we assume that it does not demand any efforts for planning.

IV. SIMULATION MODEL

A. Numerical Optimization Method

For given N BSs, by applying Monte-Carlo method, we estimate λ and ν by simply averaging λ_c and ν_c from 100 different BS location realizations. In each simulation run, we generate (optimize) BS location l for the case of the self-deployment (planned-deployment). In the case of the planned-deployment, we apply a well-known heuristic simulated annealing [11] to find the sub-optimal BS locations. This can yield near-optimum performance which serves as an approximate upper bound on the performance as a reference for comparison.

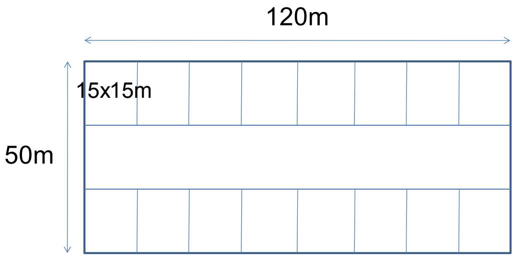

Fig. 1. Indoor office layout for a closed environment.

Then, we optimize **p** and **f** in both deployment strategies. For mathematical approximation, we first discretize irregular continuous area Ω into K measurement points as used in the grid-installation. Then, we numerically evaluate the rate and SINR over the K points. Also, we quantize p_i into n_p discrete levels. Then, we reformulate the joint transmit power and frequency control problem into a discrete optimization problem which selects the best power-frequency profile out of $n_p n_f$ possible combinations. Since the considered problem still has $\nu_c \leq \delta$ constraint, we need a procedure for checking the feasibility of the problem. Therefore, we divide this problem into two subproblems with different objectives: 1) minimizing ν_c until it finds a feasible power-frequency profile and 2) maximizing λ_c subject to $\nu_c \leq \delta$. Once the first subproblem finds a feasible profile, the second subproblem is triggered from the identified feasible power-frequency profile. Otherwise, the first subproblem terminates by simply returning the minimum estimated ν_c.

For each subproblem, we apply an iterative constrained random search algorithm [12]. The brief description of the algorithm is provided as follows:

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Initializing: all BSs randomly select an initial power-frequency profile.
Repeat:
  1) Randomly choose one of BSs, say $i$.
  2) For the selected BS $i$:
     a) Randomly choose a power-frequency profile that improves the objective and satisfy a constraint if it exists.
     b) If it does not have any better solution, it simply persists the previous profile.
Until: if the objective function converges[1] or the number of iteration exceeds a threshold, it stops the iteration.
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B. Simulation Environment

We consider an indoor office environment recommended in [13], and its layout is shown in Fig. 1. It consists of sixteen 15 m by 15 m cubics which are arranged along the side of the 6000 m^2 rectangular shape of service area. A channel gain between a receiver and a BS is only distance-dependent and

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[1] The algorithm is known to converge within a finite number of iteration [12]

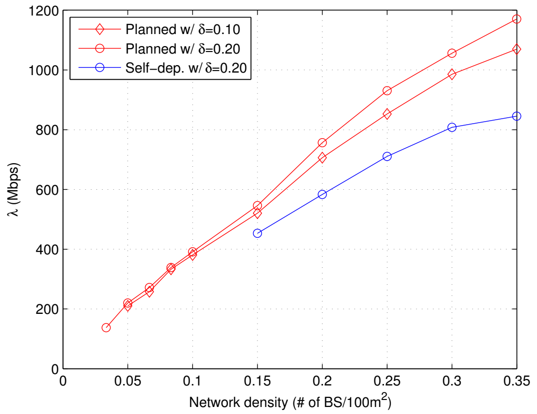

Fig. 2. Average network throughput as a function of network density for different outage thresholds (L_w=15 dB, n_f=1). Note that the self-deployment is infeasible in the entire evaluated network density when δ=0.1

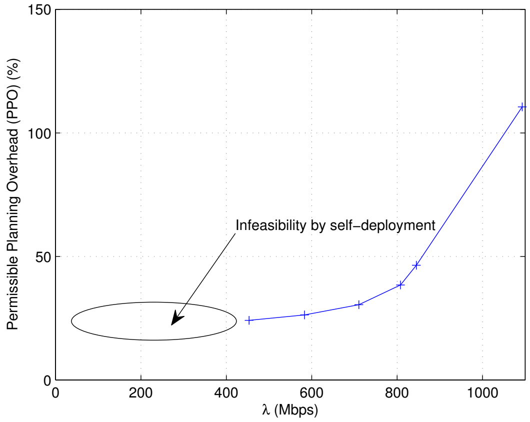

Fig. 4. Permissible planning overhead for the planned network (L_w=15 dB, δ=0.2, n_f=1). Note that higher PPO means that planned-deployment is more preferable.

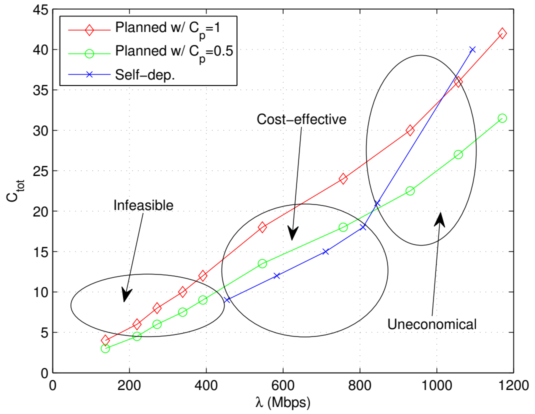

Fig. 3. Total deployment cost in a closed environment (L_w=15 dB, δ=0.2, n_f=1).

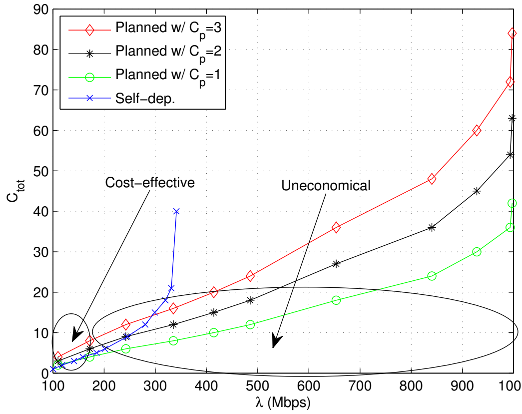

Fig. 5. Total deployment cost in an open environment (L_w=0 dB, δ=0.05, n_f=1).

is given by $PL_w = 37 + 30\log_{10}(d) + kL_w$ [14]. Note that d, k, and L_w represent a distance from a BS, the number of penetrated internal wall, and the wall loss, respectively. p_i is selected from as a set $\{-\infty\} \cup \{-20 : 2 : 20\}$ dBm, and γ_t is fixed to 3 dB. M BS candidate points are equally spaced by 10 m while K measurement points are evenly arranged by 5 m. Also, the minimum separation between adjacent BSs in the self-deployment is set to 5 m. Total system bandwidth W is given with 10 Mhz and W_i assigned to each BS is obtained by $\frac{W}{n_f}$.

V. NUMERICAL RESULTS

A. *Differentiable Deployment Regions*

Fig. 2 shows how λ changes as the number of deployed BSs increases when $n_f = 1$. The result shows that the self-deployed network is more sensitive to δ. In the case of $\delta = 0.10$, the self-deployed network is infeasible in most of the evaluated density whereas the planned network mostly remains feasible. When δ is relaxed to 0.20, the feasible region of the self-deployed network appears, but low BS density still does not fulfill the δ constraint. λ of the self-deployed network also increases as the network density increases with the aid of interference mitigation technique. However, it provides less λ than the planned network for a given network density.

By assuming $C_r = 1$ without the loss of generality, we can simply compare C_{tot} of two deployment strategies for different C_p as illustrated in Fig. 3. In particular, when C_p is fixed to 0.5, we can identify three distinct deployment regions: 1) *infeasible*, 2) *cost-effective*, and 3) *uneconomical*. In the infeasible region (150 Mbps–450 Mbps), the self-deployment does not fulfill the coverage constraint so that planning BSs is desired. When the self-deployed network can satisfy the given coverage constraint, the region is divided into two cases from the cost perspective. The cost-effective region (450 Mbps–820 Mbps) represents the range of λ where the self-deployed network is relatively economical than the planned network. When the deployment density is high, the self-deployed BSs are placed at the proximity of adjacent BSs with high probability. As a result, they are more likely to be in OFF state to reduce outage caused by high interference than the planned BSs. Thus, uneconomical region (after 820 Mbps) starts to appear in which redundant self-deployed BSs in

OFF state become dominant so that the planned network is preferable. Note that the relative size of each region varies depending on C_p. Higher C_p enlarges the cost-effective region of the self-deployed network.

Thus, when λ is given in Fig. 2, let $N_p(\lambda)$ and $N_s(\lambda)$ stand for the number of deployed BSs for the planned and the self-deployed network, respectively. Then, we can compute the extra number of self-deployed BSs by $\Delta N(\lambda) = N_s(\lambda) - N_p(\lambda)$. In order that the self-deployed network is cost-effective, $\Delta N(\lambda)C_r$ should be less than the total planning cost $N_p(\lambda)C_p$. From this condition, we can define permissible planning overhead (PPO) for a given λ and C_r as

$$\text{PPO}(\lambda) := \frac{\Delta N(\lambda)}{N_p(\lambda)} C_r \times 100\ (\%).$$

For example, 50% PPO means that the planned network is economical as long as $C_p \leq 0.5$. Otherwise, the self-deployed network is economical. Fig. 4 illustrates how PPO changes depending on λ for a given $C_r = 1$. It indicates that the planned-deployment becomes more preferable as λ increases. This is because the self-deployed network has more redundant BSs in OFF state to meet the coverage in denser deployment.

B. Shadowing and Multichannel Effects

When the indoor environment is an open area such as department stores or stadiums, wall shadowing effects shrink. By setting $L_w = 0$, we evaluate the shadowing effects as shown in Fig. 5. It shows that tighter coverage constraint, i.e., $\delta = 0.05$, can be easily satisfied and infeasible region is hardly noticeable. Since the signal from a BS is easily reachable to most of the service area without barriers, the service area hardly has coverage hole which typically occurs in environments with plenty of wall shadowing. However, the further signal propagation also creates higher interference so that many BSs are in OFF state to reduce interference to meet the coverage constraint. As a result, λ of the self-deployed network drastically diminishes as well. Even with very high planning cost, e.g., $C_p = 3$, the self-deployment cannot be cost-effective in most of evaluated regions in the figure. To sum up, we have the smaller infeasible region but the larger uneconomical region as the internal wall shadowing fades out. From this observation, we can find that the self-deployment is a suitable solution in a highly shadowed environment.

In order to reduce the interference, we can consider frequency selection by dividing whole frequency bandwidth into multiple sub-bands. Then, the self-deployed network can be feasible with tighter δ since more BSs transmit with higher power while not interfering each other. This means that infeasible region is reduced and the need for turning off the BSs also decreases. Thus, frequency selection can make the self-deployed network an economical solution when δ is tight despite of sacrificing full frequency reuse gain. We omit the quantitative result of this case due to the limitation of space.

VI. CONCLUSION

We analyzed the total deployment cost and the technical feasibility of a self-deployed network when comparing with a planned network. For this, we compare quasi-randomly placed BSs with near-optimally deployed BSs by employing transmit power control and frequency selection which are typically ignored in techno-economic studies. Then, we estimated the average network throughput subject to a coverage constraint and the total deployment cost of two deployment strategies.

For a given planning cost per BS, we identified that there are three distinct deployment regions of the self-deployed network comparing with the planned network: 1) infeasible (when the coverage constraint is tight), 2) cost-effective (when required network throughput is moderate) and 3) uneconomical (when high network throughput is demanded). Consequently, deployment decision makers should have different strategies according to required network throughput as well as a coverage constraint. Furthermore, we observed that the self-deployed network is more useful in an environment with plenty of wall shadowing than in an open area. While a centralized interference management was employed, the analysis under distributed interference mitigation remains as future work.

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