An Efficient Cost Performance Placement of Macro Sites and Small Cells Under Restricted Topology

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Abstract. The global COVID-19 pandemic leads people to intermittent quarantines and lockdowns. Many large and crowded gatherings were postponed or even cancelled to prevent social distance violation. The paper aims to tackle the placement problem of macro sites, microcells and picocells under a restricted network topology. The cell placement problem is defined based on linear programming. The algorithm named Cost Efficiency algorithm is proposed to construct a network with higher performance and lower cost. Simulation results showed that the proposed algorithm yields higher SINR value and more number of served users over construction cost compared with other planning algorithms. The result of this work is expected to help users have better network service quality when they are isolated in hospital or self-health monitoring at home.

Keywords: Cost performance index · Network planning · Relay network · Restricted network topology · Signal-to-interference-plus-noise ratio · Small cell

1 Introduction

Relay technique not only extends the signal coverage of macro site but also improves the communication quality of users in small cells. Relay network has been investigated in various mobile network technologies, such as mobile multi-hop relay network in IEEE 802.16j [1], relay nodes in LTE-Advanced network [2], and small cells in heterogeneous network (HetNet) [3]. Relay placement is complicated in mobile networks since small cells are heterogeneous to macro site [4].

In IEEE 802.16j, transparent and non-transparent relay stations are deployed to extend base station's coverage [5]. In LTE-Advanced relay network, different types of

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relay nodes are utilized to strengthen and improve eNB's signal and communication range [6]. Type 1 inband relay nodes can be deployed to extend cell range [7]. Small cell can be classified into microcell, picocell and femtocell on the basis of cell's transmission range. In general, a micro site provides communication range around several kilometers and microcell's transmission radius is around half one kilometer. Without loss of generality, picocell and femtocell are less than hundred meters. However, network providers trade cell's communication range off against the construction cost [8].

In this paper, the placement problem of multiple micro sites, microcells and picocells under a restricted network topology is considered and solved. The planning problem of a HetNet is formulated based on linear programming. A novel planning algorithm named Cost Efficiency algorithm is proposed to maximize network performance such as the number of served users and the signal-to-interference-plus-noise ratio (SINR) value. A realistic planning case and simulation-based results are given to prove the technical contribution of this work. The main contributions of the paper are summarized in the following.

- The placement problem of multiple macro sites, microcells and picocells is formulated on the basis of graph theory and linear programming.
- The Cost Efficiency algorithm is proposed to maximize the ratio of SINR value and number of served users over construction cost.
- The planning result of a large-scale network as well as 900 km^2 contains several restricted areas is showed and discussed.
- Simulation-based results prove that the proposed Cost Efficiency algorithm outperforms other planning algorithms in terms of SINR value, the number of served users, network capacity, and construction cost.

The rest of the paper is organized as follows. Section 2 surveys the related works of relay technique in mobile networks. Section 3 introduces the network model and problem formulation. In Sect. 4, the proposed algorithm is explained. Simulation results are shown in Sect. 5. Section 6 concludes the paper and provides the future direction of this work.

2 Related Works

Small cell deployment has been widely studied in recent years [9], such as handover algorithm [10], coverage extension [11], safety relays [12]. In [13], the researchers proposed a soft frequency reuse scheme to enhance edge user coverage and improve network performance. The researchers in [14] utilized small cells to improve the signal dead zone. In [15], the researchers proposed backhaul traffic models to optimize the energy efficiency of small cell backhaul networks. However, it is a trade-off problem between network performance and construction cost [16]. It is difficult to achieve cost economized and performance improved at the same time [17].

The most relevant works to this paper are [18–20]. In [18], the Supergraph Tree algorithm was proposed to achieve construction cost economized. However, the Supergraph Tree algorithm cannot guarantee the network performance of planning result.

Therefore, the Set Covering algorithm in [19] was proposed to enhance the network performance. Although the Set Covering algorithm improves network capacity, it also raises construction cost. In [20], the Tree with Type 1 and Type 1a relay algorithm was proposed to eliminate communication interference and decrease construction cost. However, the Tree with Relay algorithm cannot achieve the highest ratio of network performance over cost. As a result, the Cost Efficiency algorithm is proposed to accomplish the trade-off problem between network performance and construction cost at the same time.

3 Problem Definition

The network model is formulated as an undirected graph based on tree structure. Let V be the set of vertex include candidate positions (CPs) and user equipment (UE), and E be the set of edges between vertex. Table 1 lists the definition of notations.

Table 1. Definition of notations

Variable	Definition
G	Planned field of interest
V_1	Set of CPs in G
m	Number of CPs in G, $m = \|V_1\|$
V_2	Set of UEs in G
n	Number of UEs in G, $n = \|V_2\|$
E_1	Set of links within V_1
E_2	Set of links between V_1 and V_2
c_i	Construction cost of deployed cell on CP
$x_{i,j}$	Available links within V_1
$a_{i,k}$	Available links within V_1 and V_2
$w_{i,k}$	Signal quality of a UE in a CP
$y_{i,k}$	Hop count limitation
E_1^l	Depth of the routing tree within l
δ	Minimum user utility required
η_i	Maximum depth l of routing tree

Given an undirected graph $G = (V, E)$, where $V = V_1 \cup V_2$ and $E = E_1 \cup E_2$. Let V_1 be the subset of CPs and V_2 be the subset of UEs. Let E_1 be the subset of links between CPs in V_1, and E_2 be the subset of link between CP and UE. If a cell is deployed on the CP corresponding to z_i, it is defined as

$$z_i = \begin{cases} z_{macro}, \text{ if macro site deployed} \\ z_{micro}, \text{ if microcell deployed} \\ z_{pico}, \text{ if picocell deployed} \\ 0, \text{ otherwise} \end{cases}, \forall i \in V_1. \tag{1}$$

Note that $z_i = 0$ when not deployment on CP z_i. Thus, $z_i \in \{0, z_{macro}, z_{micro}, z_{pico}\}$. The construction cost of different kinds of cells are different and defined as

$$c_i = \begin{cases} c_{macro}, \text{ if macro site deployed} \\ c_{micro}, \text{ if microcell deployed} \\ c_{pico}, \text{ if picocell deployed} \\ 0, \text{ otherwise} \end{cases}, \forall i \in V_1. \tag{2}$$

Note that $c_i = 0$ while not deploying cells on CP z_i. Thus, the construction cost $c_i \in \{0, c_{macro}, c_{micro}, c_{pico}\}$.

Let $x_{i,j}$ be the available link between CP z_i and CP z_j, where

$$x_{i,j} = \begin{cases} 1, \text{ if}(z_i, z_j) \in E_1 \text{and} z_i \cdot z_j \neq 0 \\ 0, \text{otherwise} \end{cases}, \forall i, j \in V_1. \tag{3}$$

If $x_{i,j} = 1$, it means that the link between CP z_i and z_j is valid, and vice versa. To describe the coverage of a specified UE q_k, the variable $a_{i,k}$ is defined as

$$a_{i,k} = \begin{cases} 1, \text{if } (z_i, q_k) \in E_2 \\ 0, \text{if } (z_i, q_k) \notin E_2 \end{cases}, \forall i \in V_1, \forall k \in V_2. \tag{4}$$

If $a_{i,k} = 1$, it means that the link between CP z_i and UE q_k is valid, and vice versa. For receiving signal, a UE must be served by a specific cell at least. As a result, we assume that the UE q_k is directly served by a macro site or receives signal from microcell or picocell which relays from a micro site. The signal quality $w_{i,k}$ of UE q_k is defined as

$$w_{i,k} = \begin{cases} w_{macro}, \text{if } a_{i,k} = 1 \wedge z_i = z_{macro} \\ w_{micro}, \text{if } a_{i,k} \cdot x_{i,j} = 1 \wedge z_i = z_{micro} \\ w_{pico}, \text{if } a_{i,k} \cdot x_{i,j} = 1 \wedge z_i = z_{pico} \\ 0, \text{otherwise} \end{cases}, \tag{5}$$

where $\forall i, j \in V_1, \forall k \in V_2$. Therefore, the utility of a specified UE q_k is $u_k = max_k w_{i,k}$.

In addition, the tree structure should be restricted and formulated as

$$\sum\nolimits_{e \in E(S)} x_e \leq |S| - 1. \tag{6}$$

where $S \subseteq V_1$ and $E(S) = \{(i,j) \in E_1 | i, j \in S\}$. Since two-hop relaying is considered in this work, the depth of routing tree should be defined as

$$y_{i,k} = \begin{cases} 1, \text{if } (z_i, q_k) \in E_1^l \\ 0, \text{if } (z_i, q_k) \notin E_1^l \end{cases}, \forall i \in V_1, \forall k \in V_2. \tag{7}$$

Let $\eta_i = max_j y_{i,k}$ and define η_i should be greater than or equal to 1 and less than or equal to 2.

The planning problem with considering multiple macro sites, microcells and picocells deployment for a HetNet is formulated as follows.

Maximize

$$\sum\nolimits_{i=1}^{m}\sum\nolimits_{k=1}^{n}\frac{z_i\cdot w_{i,k}}{c_i}, \tag{8}$$

Subject to

$$\sum\nolimits_{i=1}^{m} z_i \geq 0, 0 \leq z_i \leq m, \forall i \in V_1, \tag{9}$$

$$\sum\nolimits_{i=1}^{m}\sum\nolimits_{k=1}^{n} w_{i,k} = a_{i,k}\cdot y_{i,k}\cdot w_{i,k}, \tag{10}$$

$$\sum\nolimits_{i=1}^{m} c_i \leq m \times c_{macro}, \forall i \in V_1, \tag{11}$$

$$\sum\nolimits_{e\in E(S)} x_e \leq |S| - 1. \tag{12}$$

$$\sum\nolimits_{k=1}^{n}\frac{u_k}{n} \geq \delta, \forall k \in V_2. \tag{13}$$

$$1 \leq \eta_i \leq 2, \forall i \in E. \tag{14}$$

The primary goal is to maximize the ratio of served user and SINR value over construction cost, which is captured in Eq. (8). Constraint (9) guarantees micro sites and small cells are deployed. Constraint (10) guarantees users are served by cell deployed. Constraint (11) guarantees the construction cost of deployed cells not exceed the maximum construction cost while deploying macro sites on all CPs. Constraint (12) restricts the network topology to tree structure. Constraint (13) guarantees that all served users are provided with minimum utility rate required. Constraint (14) guarantees the planning result is two-hop relaying.

4 Proposed Cost Efficiency Algorithm

In this section, the Cost Efficiency algorithm is proposed to tackle with the placement of macro sites, microcells and picocells. The notations in the algorithm are explained as follows. A descending order list $S = f_d(G, X, Y)$ is used to generate the adjacent vertices in Y of elements in X. If vertexes are in same degree, the sequence can be arbitrary. The notation $S[i]$ represents the i-th vertex in the list S. The notation $N(G, x)$ represents the set of neighbor vertices of vertex x in graph G. The notation $\gamma(G, X)$ represents the vertex-induced subgraph of G with the complementary set $V \backslash X$. Let $BFS(G, x)$ be a subgraph roots at the vertex x and applies breath-first-search approach. The notation $U(z)$ represents the average utility of served users. The notation $f_{BFS,l,macro}(G)$ represents the graph constructed by adopting l-depth breadth-first-search on graph G from a deployed macro site.

The proposed Cost Efficiency algorithm is captured in Algorithm 1. Line 1 initializes the placement configuration. Line 2 to line 7 arranges CPs in a descending order list in accordance with the number of served UEs. Note that a selected CP and its served UEs forms a subgraph. Line 8 to line 13 deploys microcell on an unselected CP to connect the subgraphs. A CP connects the most other CPs will be selected to deploy a macro site when more than one CP are connected with each other. Line 14 to line 20 guarantees all served UEs are satisfied with their minimum utility rate. If the utility rate of a served UE is less than its minimum utility rate, a picocell will be deployed to replace the current deployed cell. Line 21 to line 26 guarantees the placement result follows tree structure and does not violate hop count limitation. Lastly, the placement result of a given network topology includes micro sites, microcells and picocells is obtained.

Algorithm 1: Cost Efficiency Algorithm

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Input: $G$: given undirected graph
       $z$: placement of macro site, microcell and picocell
       $\delta$: minimum user utility required
       $l$: maximum routing tree length
01 $\Omega_1 = V_1, \Omega_2 = V_2, \Delta = \emptyset, l = 2$
02 repeat
03     $S = f_d(G, \Omega_1, \Omega_2)$
04     $\Delta = \Delta \cup S[1]$
05     $\Omega_1 = \Omega_1 \backslash S[1]$ and $\Omega_2 = \Omega_2 \backslash N(G, S[1])$
06 until $\Omega_2 = \emptyset$
07 $G_r = \gamma(G, \Omega_1), where\ G_r = (V_{G_r}, E_{G_r})$
08 while $G_r$ is unconnected
09     $S = f_d(G, \Omega_1, V_{G_r})$
10     $z_{S[1]} = z_{micro}$
11     $G_r = \gamma(G, \Omega_1 \backslash S[1])$
12     $z_{V_{G_r}} = z_{macro}$
13 $\Omega_3 = \emptyset$, $G_{r'} = G_r$
14 while $V_{G_r} \neq \emptyset$ and $U(z) < \delta$
15 repeat
16     $S = f_d(G_r, V_{G_r}, \Omega_2)$
17     $z_{s[1]} = z_{pico}$
18     $\Omega_3 = \Omega_3 \cup \{S[1]\}$
19     $G_r = \gamma(G_r, S[1])$
20 until $U(z) \geq \delta$
21 repeat
22     $G^l = f_{BFS,l,macro}(G_r), where\ G^l = (V^l, E^l)$
23     if $V^l \neq \Delta$
24         $S = f_d(G_r, \Delta \backslash V^l, V_2)$
25         $z_{s[1]} = z_{macro}$
26 until $V^l = \Delta$
27 Output the placement results of a given $G$
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5 Simulation Results

Simulation is conducted by MATLAB [21] to construct network topology and planning algorithms. Parameters in simulation are listed in Table 2. Firstly, we assume that all locations of CPs and UEs are known so that algorithms decide to deploy cells on CPs for covering UEs. The range of micro site, microcell and picocell is set to 3, 0.5, 0.2 km respectively. According to [22, 23], the construction cost of micro site, microcell and picocell is defined as 20, 3 and 1 unit respectively. The simulation results are obtained and averaged from 10 different network topologies. The analyzed performance metrics include construction cost, number of served users, network capacity, and average SINR value of each user. The proposed Cost Efficiency algorithm is compared with three algorithms, i.e., the Supergraph Tree in [18], the Set Covering algorithm in [19], and the Tree with Relay algorithm in [20].

Table 2. Simulation parameters

Variables/Parameters	Value
Network size	30×30 (km)
Number of restricted zone	10
Number of candidate position	100
Number of user equipment	1000
Macro site's range radius	3 (km)
Microcell's range radius	500 (meter)
Picocell's range radius	200 (meter)
Macro site's construction cost	20 (unit)
Microcell's construction cost	3 (unit)
Picocell's construction cost	1 (unit)
Macro site's transmission power	46 (dBm)
Microcell's transmission power	32 (dBm)
Picocell's transmission power	15 (dBm)
Propagation model	-174 (dBm/Hz)
Noise power	2×10^{-14}(W)
Bandwidth	10 (MHz)

The average construction cost of four algorithms in 10 planning results is captured in Fig. 1. It can be observed that both of the Set Covering algorithm and the Tree with Relay algorithm spend higher construction cost compared with other algorithms. The Set Covering algorithm yields the highest construction cost because it aims to serve more users that results in the most macro site deployment. The Supergraph Tree algorithm aims to minimize construction cost but results in the lowest number of served users. Although the proposed Cost Efficiency algorithm spends more cost than the Supergraph Tree algorithm, it achieves significantly higher number of served users.

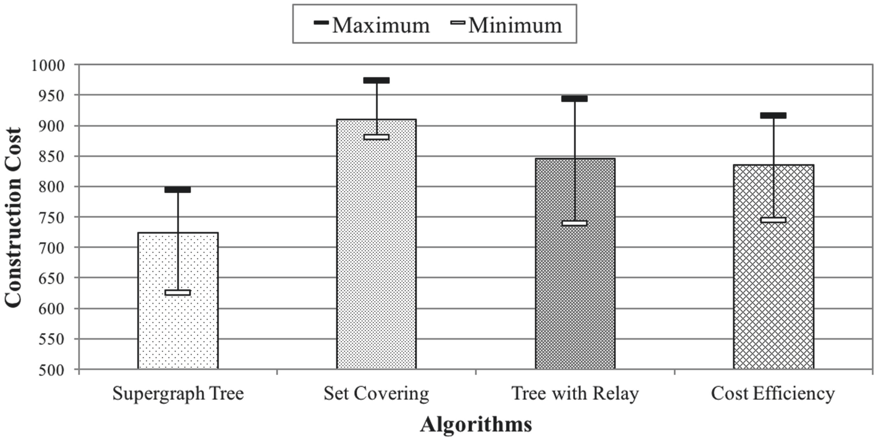

Fig. 1. Average construction cost of four algorithms.

The average number of served users in 10 planning results is captured in Fig. 2. It can be observed that the Set Covering algorithm and the proposed Cost Efficiency algorithm yield more served users compared with the other two algorithms. Although the Supergraph Tree algorithm economizes construction cost, it cannot guarantee more served users. Compared to the Set Covering algorithm, the Cost Efficiency algorithm achieves slightly fewer served users but lower construction cost significantly.

The average network capacity of four algorithms in 10 planning results is captured in Fig. 3. It can be observed that the Set Covering algorithm and the proposed Cost Efficiency algorithm achieve higher network capacity compared with the other two algorithms. The Supergraph Tree algorithm obtains lower network capacity because it serves the lowest number of served users. The Tree with Relay algorithm obtains the lower network capacity because it constructs the planning result with worse SINR value. The Cost Efficiency algorithm yields the similar network capacity with slightly less served users compared to the Set Covering algorithm. It is attributed to the fact that the Cost Efficiency algorithm serves users by deploying microcells and picocells with better SINR value for achieving higher network capacity.

The average SINR value of four algorithms in 10 planning results is captured in Fig. 4. It can be observed that the proposed Cost Efficiency algorithm achieves the highest SINR value compared with other algorithms. The Cost Efficiency algorithm deploys cheaper microcells and picocells to provide better communication quality so

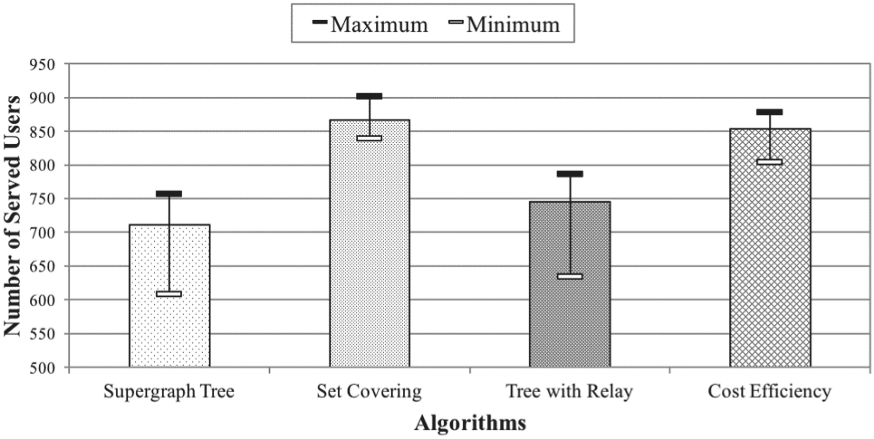

Fig. 2. Average number of served users in 10 planning results.

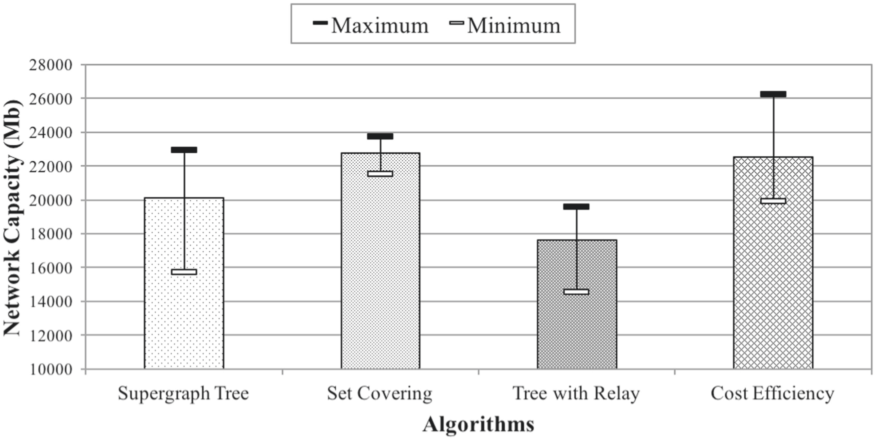

Fig. 3. Average network capacity of four algorithms.

that it accomplishes higher network capacity by serving more users with the highest SINR value. In summary, it not only uses lower construction cost to serve more users but also yields the best communication quality.

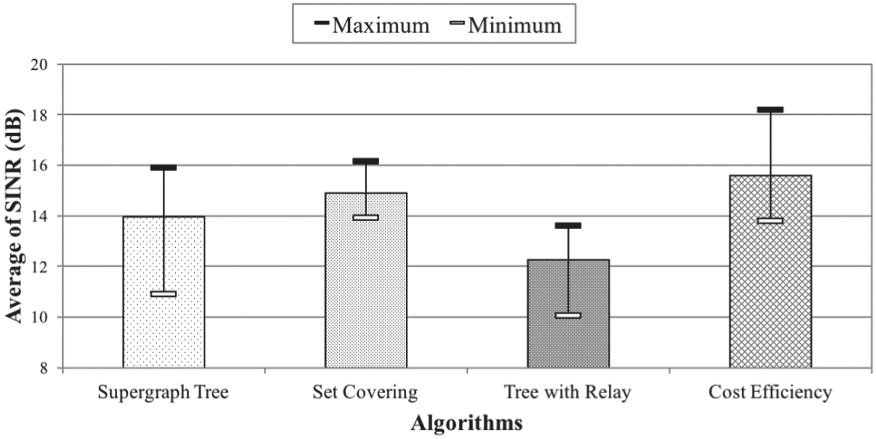

Fig. 4. Average SINR value of all served users.

6 Conclusion and Future Work

Due to the COVID-19 pandemic worldwide, people are isolated in the hospital and self-managed at home. Network planning problem changed from an open field of interest to a restricted terrain. In this paper, the placement problem of macro sites, microcells and picocells is investigated under a restricted network topology. The proposed Cost Efficiency algorithm aims to construct a planning result with higher network performance and lower construction cost. Results showed that the Cost Efficiency algorithm outperforms other planning algorithms in terms of the cost performance index of served users and SINR value over construction cost. In the future, we intend to study the network planning result of more performance metrics.

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