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A Coverage-Based Location Approach and Performance Evaluation for the Deployment of 5G Base Stations

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ABSTRACT It has become a strategic consensus of the international community for accelerating the deployment of 5G network. This paper presents an approach for the deployment of 5G base stations under the considerations of both the cost and the signal coverage. We formulate an optimization problem for the site selection and location of 5G macro and micro base stations. An implementation procedure is proposed in the paper for the cooperative operation and deployment scheme of optimizing the location of 5G heterogeneous base stations, which aims to optimally reduce the setup cost and strengthen the signal coverage while deploying 5G base stations. A series of numerical examples are solved in the paper to demonstrate the proposed approach, and a cost-benefit analysis is also conducted to determine the optimal deployment plan for the number of macro and micro base stations. In the conclusion, a balanced executable solution is presented to make the signal strength of all demand points in the studied 5G network reach the strongest under the budget constraint.

INDEX TERMS 5G network optimization, computational intelligence, cost benefit analysis, heterogeneous network, algorithm design and analysis, decision making.

I. INTRODUCTION

The fifth-generation (5G) network is in a critical period of technological standard formation and industrialization cultivation [1]–[3]. Most countries in the world regard 5G as a priority development area in national digital strategies, which can strengthen industrial layout and shape new competitive advantages [4]–[6]. The International Telecommunications Union (ITU) defined three major scenarios of 5G applications, including Enhanced Mobile Broadband (eMBB), massive Machine Type Communications (mMTC), and Ultra-Reliable Low-Latency Communication (URLLC) [7].

The famous consulting firm Deloitte predicts that the total investment in the global 5G industry chain will reach 3.5 trillion US dollars, and industry application sales driven by 5G technology will reach 12 trillion US dollars from 2020 to 2035. It is also predicted that the average annual investment scale of the global 5G value chain will reach 200 billion US dollars, and the output of the global 5G value chain will reach 3.5 trillion US dollars by 2035 [8].

In China, the Chinese central government has involved 5G in its national strategy, which is viewed as one of the key points in the national innovation strategy implementation. China plans to build 1 to 1.1 million 5G base stations and expand the coverage of 5G networks to more than 330 cities in 2020. In the next 5 years (2020-2025), such a large-scale investment in 5G network deployment will reach 130 billion to 218 billion US dollars, which is by far the largest investment in the world.

The management scheme for base stations is to meet the users' requirements for 5G network data transmission in the planning area, and build a transmitting base station at

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a suitable location so that the 5G network signal covers the entire planning area [9]–[14]. Connections using the 5G network are typically generated by a very large population of users independently communicating with an equivalently large population of servers and correspondents for a variety of applications. According to traffic demand and network management settings, it requires suitable bandwidth to individual connection to achieve guaranteed Quality of Service (QoS) level [15], [16]. Key issues in the design of 5G networks include providing suitable bandwidth to meet connections' QoS requirements, and achieving that goal in an efficient manner [17]–[20]. The network provider chooses an optimal scheme for the different users under the total budget to fulfill requirements of connections [21]–[23]. In addition, due to lack of resources, the risk of rejecting connection requests is supposedly kept below a negotiated level [24]–[26].

Furthermore, the decision making in terms of the dynamics of the cell selection process could be considered via a game theoretic approach, such as [27] and references therein. The deployment of the base stations could also depend on the pricing mechanisms used by the Internet service providers [28]. The optimal assignment of network users to the most appropriate cell could maximize their QoS-aware performance [29].

Several existing works used macro base stations to cover large areas to ensure basic communication requirements and satisfy users' QoS requirements [30]–[32], but they cannot effectively reduce deployment costs. If the macro base stations are deployed intensively in a large area to ensure a good user experience, the high deployment and maintenance costs will be incurred. The more the macro base station is built, the wider the coverage area and the stronger the signal strength will be improved, while the overall cost of building a station will increase. Therefore, a trade-off issue exists between signal strength and cost while implementing the establishment of 5G macro and micro base stations.

In this paper, we aim to solve this problem flexibly at a lower economic cost. Taking into account both cost and signal coverage, we propose an optimization scheme for the establishment and cooperative operation of 5G macro and micro base stations. In our management scheme, the micro base stations can be deployed within the coverage of the macro base stations, and both operate at the same time. Because of the low cost and small coverage of micro base stations, they can be deployed to increase the signal coverage of densely populated areas in multiple small areas. The macro base station plays a role in ensuring the basic signal, and the micro base station is deployed to solve the low users' experience.

Due to the present work, we will find an approach to balance the benefits from a heterogeneous 5G network by compensating for the high setup cost of macro base stations through the low cost of micro base stations. In addition, a relatively balanced feasible solution is also presented to make the signal strength of all test points in the studied 5G network reach the strongest via using the micro base stations to compensate for the low signal strength along the edge of the macro base station.

The main contribution of the present work is to formulate the problem of the deployment of 5G heterogeneous base stations as an optimization model. In addition, an executable approach is figured out to solve the problem under the budget constraint. A cost-benefit analysis is also going to be conducted to determine the optimal deployment plan for the number of macro and micro base stations by solving a series of numerical examples. The proposed coverage-based location approach is demonstrated in a stepwise manner for optimizing the location of 5G heterogeneous base stations.

The originality of our work lies in the derivation of a mixed-integer nonlinear optimization model with two objective functions for the site selection and location of 5G macro and micro base stations. Moreover, the proposed coverage-based location approach can achieve both the minimum of deployment cost and the maximum of signal coverage rate in a balanced manner. The implementation procedure for the cooperative operation and deployment scheme presented in this paper can be applied in the new infrastructure of 5G base stations in China.

The structure of the paper is organized as follows. In the next section, we introduce the background and development of 5G network, especially in China. Problem definitions and an optimization scheme are to be introduced in Section III. In Section IV, a coverage-based location approach will be presented for solving the studied optimization problem in three steps of the implementation procedures. In Section V, five illustrative examples are provided to demonstrate the proposed coverage-based location approach, and a cost-benefit analysis is also conducted to determine the optimal deployment plan. The concluding remarks are summarized in Section VI.

II. DEVELOPMENT OF 5G DEPLOYMENT

Founded in February 2018 by AT&T, China Mobile, Deutsche Telekom, NTT DOCOMO and Orange, the Open Radio Access Network (O-RAN) Alliance was established as a German entity in August 2018. The introduction of Open-RAN into the 5G system is conducive to the creation of an advanced and active communication network. Up to the beginning of 2020, there have been about 22 network operators and more than 120 equipment and hardware/software suppliers participated in the O-RAN alliance for conducting design research. It enables the network operators around the world to choose diverse best-of-breed options from multi-vender solutions for their 5G deployments, which can bring more flexibility as they deploy their 5G network architecture in various deployment scenarios and geographies [33].

In April 2019, the Defense Innovation Board of the United States of America released a report stating that China, Japan, South Korea, and the United States were described as major competitors in the development and deployment of 5G networks [34]. In addition, it was reported that European countries such as Britain, Germany and France formed the second level in the deployment of 5G networks.

The launch of 5G network requires a lot of investment in new infrastructure such as antennas and base stations, so that it is possible to realize some truly exciting applications and services. It is estimated the first mover advantage on the 5G network deployment stage will appear in China because only China plans to establish a standalone 5G network in 2020, which is at least a few years before the United States and other countries in the world that set a target date in 2025.

There are several favorable conditions to support the development of 5G in China. First of all, China, as the world's most populous country and the world's second largest economy, can provide a market of sufficient scale for the development of 5G and downstream application industries. Second, it has formed a complete mobile communication ecosystem in China, which is composed of telecom operators, equipment manufacturers, parts suppliers, and downstream application providers. Third, accounting for 60% of the world's 4G base stations, China's 4G is the world's largest 4G network with the widest coverage and highest quality. The iron tower, power supply, transmission optical cable, and the computer equipment in the 4G network could be used for 5G, which is conducive to the large-scale deployment of the 5G network.

In China, the infrastructure of 5G network is an important development direction of the new generation of information technology, which is regarded as a key breakthrough area for the deployment of a strong network nation [35]. In February 2013, the Ministry of Industry and Information Technology (MIIT), the National Development and Reform Commission (NDRC) and the Ministry of Science and Technology jointly established the IMT-2020 (5G) promotion group, dedicated to promoting the research and development of 5G technologies and standards, and leading the trials for technology research and development of 5G. In January 2016, September 2016 and March 2017, they launched the three phases of test for 5G technology research and development, including key technology test, technical scheme test and system test, individually.

On January 29, 2019, the NDRC of the People's Republic of China and other nine ministries and commissions of China jointly issued the "Implementation Plan for Further Optimizing Supply, Promoting Steady Growth of Consumption and Promoting the Formation of a Strong Domestic Market (2019)," which proposed to accelerate the launch of 5G commercial license [36]. On June 6, 2019, the MIIT of the People's Republic of China issued 5G commercial licenses to China Telecom, China Mobile Communications Group, China Unicom, and China Broadcast Network. The issuance of 5G commercial licenses marks that China has been provided with the mature conditions for large-scale commercial applications and officially entered the first year of commercial 5G.

The 5G network not only can further improve the user experience, but also meet the application requirements of the Internet of Things in the future. As of the end of December 2018, the number of Internet users in China was 827 million, and the Internet penetration rate was 59.6%. In 2019, the four core indicators of 5G network technology were achieved, that is, 1-20 Gbps peak rate, 10-100 Mbps user experience, 1-10 millisecond end-to-end delay, and 1-100 times the network energy efficiency promotion. In order to ensure that the 5G network supports 1000 times of traffic growth, it is necessary to increase the number of low-power nodes and deploy various wireless nodes that exceed the current site by more than 10 times. Meanwhile, in order to keep the distance between the sites within 10m and support the service of 25,000 users per square kilometer, it requires ultra-dense heterogeneous networks.

The high density of 5G communication network will lead to a surge in the number of base stations, especially in urban areas. According to the report of the China Academy of Information and Communications Technology (CAICT) [8], the number of 5G base stations will be about 1.5 times that of 4G under the same coverage rate. The implementation of China's 5G deployment faces several practical problems, such as large demand for site resources, location selection, property access and high rents. For example, some office buildings and residential properties have an entry fee of RMB 300,000 for each 5G base station, which increases the cost of the operator.

According to the prediction of CAICT [8], the 5G users in China will reach 816 million in 2025, and the penetration for mobile users will reach around 48%. After Year 2025, the penetration rate of 5G users will accelerate in China, compared with the average annual increase of 7.4% in the first five years of commercial use. It is expected that the scale of 5G users will reach 1.5 billion in 2030, with a penetration rate of around 85%. With the active support from Chinese governments and a series of huge capital investment, a vibrant 5G industrial environment has been established in China. The industry practice and development of 5G in China can provide a demonstration for the formulation and application of global market policies.

China's 5G deployment is going to follow the following path: the key cities will be covered by macro base stations in the early stage; the urban and rural areas will be covered by macro base stations in the mid-term stage; and the hot spots will be covered by micro base stations in the later stage. The three major operators in China, China Telecom, China Mobile Communications Group, and China Unicom, are going to implement pre-commercialization on the basis of scale testing in the early stage of 5G deployment during 2019-2020, and the pilot cities for complete scale deployment will mainly focus on first-tier cities and second-tier cities.

On March 24, 2020, the MIIT of the People's Republic of China issued the "Notice on Promoting the Rapid Development of 5G", which aims to accelerate the progress of 5G deployment and strive to build a high-quality wide-coverage 5G network [37]. For cities in China, the "New Infrastructure" represented by 5G will not only become a catalyst for a new round of economic development, but also the core of soft power and competitiveness.

In summary, when a 5G network is plan to be established, it is important to introduce simplified solutions to optimize operations and determine how to effectively deploy the network at a specific level of density. Therefore, in the next section, we are going to present an optimization scheme, which aims to have enough macro and micro base stations to provide high-quality services.

III. AN OPTIMIZATION SCHEME

In this section, we present a mathematical model for optimizing the site selection for base stations while constructing a 5G network. The optimization problem to be solved in this paper is concerned with the trade-off between signal strength and cost for the deployment of 5G network. The deployment cost depends on the number of macro and micro base stations and their respective unit prices, and the signal coverage depends on the location/site selection of macro and micro base stations. An optimization scheme will be developed for optimizing the trade-off between minimizing the cost and maximizing the signal coverage through the cooperative operation of macro and micro base stations. The definitions of mathematical notations used in this paper are summarized in Table 1.

Suppose that the total number of demand points is given as N_D in a rectangular map of 5G network deployment, where N_D is a positive integer. If there are n demand points in the coverage of a certain macro base station k, it is given that the coordinate set of those n demand points is $\left\{\left(X_1^k,\ Y_1^k\right),\left(X_2^k,\ Y_2^k\right),\ldots,\left(X_{n-1}^k,\ Y_{n-1}^k\right),\left(X_n^k,\ Y_n^k\right)\right\}$, where k is the index number of macro base stations and the number n is related to the index k.

Decision variables to be determined include the number S_1 of macro base stations, and the coordinates $\left(X^k\ ,\ Y^k\right)$ of macro base stations with the unit price P_1 and signal coverage A_1, where superscript $k = 1, \ldots S_1$ denotes the index number of macro base stations. In addition, our decision variables also include the number S_2 of micro base stations to be determined, and the coordinates $\left(x_j^k\ ,\ y_j^k\right)$ of micro base stations with the unit price P_2 and signal coverage A_2, where subscript $j = 1, \ldots S_2^k$ denotes the index number of micro base stations in the coverage of the corresponding macro base station k. Note that the total number S_2 adds up the number S_2^k of micro base stations to be constructed within all possible macro base stations.

Under the consideration of both construction cost and signal strength, we derive an optimization model with mixed integer variables as follows.

$$\text{Minimize } Cost = P_1 \cdot S_1 + P_2 \cdot S_2 \tag{1}$$

$$\text{Maximize } Coverage = \frac{D_M}{N_D} \tag{2}$$

$$\text{s.t. } \sqrt{(X_i^k - X^k)^2 + (Y_i^k - Y^k)^2} \le A_1, \quad \forall i = 1, \ldots, n^k, \quad \text{and } k = 1, \ldots, S_1, \tag{3}$$

TABLE 1. The definitions of notations.

Notation	Definition
N_D	The total number of demand points in a rectangular map.
S_1	The total number of macro base stations, which is a decision variable to be determined.
S_2	The total number of micro base stations, which is a decision variable to be determined.
k	The index number of macro base stations.
n^k	The number of demand points in the coverage of a certain macro base station k.
(X^k, Y^k)	The coordinates of macro base stations.
$\left(x_j^k, y_j^k\right)$	The coordinates of micro base stations in the coverage of the macro base station k.
S_2^k	The number of micro base stations in the coverage of the macro base station k.
P_1	The unit price of a macro base station.
P_2	The unit price of a micro base station.
A_1	The signal coverage of a macro base station.
A_2	The signal coverage of a micro base station.
D_M	The number of demand points to be covered via the approach.
R_c	A preset threshold for the minimum signal coverage rate.
u_{ji}	The membership degree from a demand point $j = 1, \ldots, N_D$, to a macro base station $i = 1, \ldots, S_1$.
U	The membership matrix consists of all elements u_{ji}, where the matrix size is N_D rows and S_1 columns.
c_i	The centroid of the cluster i.

$$\sqrt{(x_j^k - X^k)^2 + (y_j^k - Y^k)^2} \le A_2, \quad \forall j = 1, \ldots, S_2^k, \quad \text{and } k = 1, \ldots, S_1, \tag{4}$$

$$D_M \le N_D, \tag{5}$$

$$\frac{D_M}{N_D} \ge R_c, \tag{6}$$

$$S_2 = \sum_{k=1}^{S_1} S_2^k, \tag{7}$$

$$S_1 \ge 1 \quad \text{and } S_2 \ge 1 \text{ are positive integers.} \tag{8}$$

Objective function (1) represents the goal for cost minimization. Objective function (2) indicates the goal for signal coverage maximization. For a given demand point within the coverage of a certain macro base station k, constraint (3) represents that its distance from the location center of this macro base station should not be larger than the signal coverage A_1. Constraint (4) indicates that the coordinate of each micro base station in the category belonging to a certain macro base station k is guaranteed to be within the range of its signal coverage A_2.

Constraint (5) ensures that the number D_M of demand points to be covered cannot exceed the total number of demand points N_D. Constraint (6) is the minimum QoS requirement which ensures the total signal coverage rate needs to be larger than or equal to a preset threshold R_c. Constraint (7) indicates that the number S_2 is the total sum of number S_2^k of micro base stations to be constructed. Constraint (8) represents that decision variables S_1 and S_2 are positive integers.

By solving the presented mathematical model, we can determine an optimal solution which reduces the deployment cost for 5G base stations and improves the signal strength of the areas where they are located. In order to efficiently solve the above optimization model, we are going to apply a heuristic algorithm for the location selection of macro and micro base stations in the next section.

IV. A COVERAGE-BASED LOCATION APPROACH

Taking into account both cost and signal strength, we are going to propose a cooperative operation and deployment scheme for locating macro and micro base stations. The low cost of the 5G micro base stations is used to compensate for the high deployment cost of the 5G macro base stations. The goal of the present approach is to achieve the minimum of objective function (1) and the maximum of objective function (2) in a balanced manner, and derive an optimal location plan for 5G base stations under the constraints (3)-(8).

A. LOCATION SELECTION FOR MACRO BASE STATIONS

In the design of solving algorithm for the location selection of macro base stations, we assume each demand point has a membership degree belonging to a certain macro base station, and the sum of the membership degree from each demand point to all macro base stations is equal to 1. The formula for calculating the degree of membership is:

$$\sum\nolimits_{i=1}^{S_1} u_{ji} = 1, \quad \forall j = 1, \ldots, N_D, \tag{9}$$

where S_1 is the number of clustering categories of macro base stations, and N_D is the total number of demand points. All elements u_{ji} form a membership matrix $\mathbf{U}$, where the size of the membership matrix is N_D rows and S_1 columns.

After calculating the distance from all demand points to the center point of each cluster, the minimum distance is kept, where the distance is calculated using the Cartesian distance formula. According to the signal coverage radius of the macro base station, we can screen out the number of demand points and their position coordinates that are not within the signal coverage of the specific macro base station. In addition, we can use the minimum distance to determine whether the demand point is within the edge area covered by a specific macro base station, and record the number of boundary points and their coordinates.

The element u_{ji} in the membership matrix $\mathbf{U}$ is updated by the following formula (10):

$$u_{ji} = \frac{1}{\sum\nolimits_{k=1}^{S_1} \left(d_{ji}/d_{jk} \right)^{2/m-1}}, \tag{10}$$

where m is the weighted index of membership, and $d_{ji} = \|c_i - x_j\|$ is the Cartesian distance between the centroid c_i and point x_j. The centroid c_i can be determined via the following formula (11):

$$c_i = \sum\nolimits_{j=1}^{N_D} \left(u_{ji}^m \cdot x_j \right) \Big/ \sum\nolimits_{j=1}^{N_D} u_{ji}^m. \tag{11}$$

The implementation procedures for the location selection of macro base stations include the following steps:

Step A1: Randomly assigned the membership value u_{ji} of each demand point j belonging to the clustering category of i-th macro base station for each $i = 1, \ldots, S_1$, and then construct a membership matrix $\mathbf{U}$, where the size of the membership matrix is the number of demand points times the number of clusters.

Step A2: Calculate the centroid c_i of each cluster according to formula (11), where the centroid c_i is the coordinate point of the i-th macro base station, for all $i = 1, \ldots, S_1$.

Step A3: Update the membership matrix $\mathbf{U}$ via formula (10).

Step A4: Repeat Step A2 and Step A3 until the absolute value of all membership changes is lower than a given threshold.

Output: The centroid c_i of the cluster, for all $i = 1, \ldots, S_1$. That is, the coordinate points of the macro base stations.

B. LOCATION SELECTION FOR MICRO BASE STATIONS

In this subsection, we use a clustering algorithm for finding the initial micro base station location.

The implementation procedure procedures for the location selection of micro base stations include the following steps:

Step B1: Randomly assigned the coordinate points of S_2^k initial micro base stations, for each cluster $k = 1, \ldots, S_1$.

Step B2: Determine all the edge points and noise points outputted from the algorithm (Steps A1-A4) in the previous subsection, and assign each of those points into the coverage area of the nearest macro base station, where noise points are the demand points that are not within the coverage area of any macro base station.

Step B3: Calculate the average value of each cluster $k = 1, \ldots, S_1$, and then use it as the new coordinate point of micro base station.

Step B4: Repeat Step B2 and Step B3 until the coordinates of those S_2^k micro base stations no longer change.

Output: The coordinate points of S_2^k micro base stations, and signal category of each cluster $k = 1, \ldots, S_1$.

C. FINE-TUNE THE NOISE POINTS

If there exist noise points that are not covered by the macro base station, we will fine-tune the initial coordinates of the micro base station obtained from the algorithm (Steps B1-B4) in Subsection B, where the noise points are those signal test points that are not within the coverage of the macro base station. We move those noise points whose coordinates are outside the coverage of the macro base station to an appropriate position, and keep the full coverage of the boundary points and the signal coverage ratio greater than a preset value.

The implementation procedure of this fine adjustment for the location of micro base station includes the following steps:

Step C1: Calculate the distance of all initial micro base stations from each macro base station, and then keep the minimum value.

Step C2: If the minimum value is within the coverage radius of the macro base station, there is no need to adjust the position, and this procedure ends. Otherwise, go to the next step.

Step C3: Record the initial coordinates of the micro base station and which macro base station it belongs to, as well as the original clustering category.

Step C4: Construct a circle function of the coverage radius for each macro base station, and derive a linear function of the micro base station and the affiliated macro base station.

Step C5: Calculate the solution of the circular function and the linear function, and then take the smaller intersection point as the candidate coordinate point of the micro base station.

Step C6: Calculate the distance between the candidate coordinate point and all demand points of the corresponding signal category for this micro base station.

Step C7: If a demand point falls within the signal coverage radius of the micro base station, this candidate coordinate point is retained and go back to Step C2. Otherwise, this candidate coordinate point is abandoned and there is no need to adjust this macro base station, and then go back to Step C1.

Output: The final location address of micro base station.

D. THE OVERALL PROCEDURE OF OUR APPROACH

A relatively balanced optimal solution can be obtained through the following implementation procedures, which forms a heterogeneous 5G network to balance the benefits.

The overall process of our approach for solving the studied optimization problem is summarized as follows.

Step 1: Collect the coordinate set of demand points, the unit price and signal strength of 5G macro base stations, and the unit price and signal strength of 5G micro base stations.

Step 2: Construct a network optimization model (1)-(8) with mixed integer variables.

Step 3: Apply Steps A1-A4 for determining the location of 5G macro base stations.

Step 4: Apply Steps B1-B4 for determining the initial location of 5G micro base stations.

Step 5: Apply Steps C1-C7 for fine-tuning the coordinates of the 5G micro base stations, move the coordinates of those points outside the coverage of the 5G macro base station to a suitable position, and keep the coverage rate of the boundary points and the noise points greater than a default value.

By conducting the above scheme, it constitutes a heterogeneous 5G network where the macro base stations and the micro base stations operate cooperatively. In the proposed approach, we use Step 3 to determine the location address of 5G macro base stations, and use Step 4 to select the initial 5G micro base stations. Finally, Step 5 is used to supplement the shortcoming of poor coverage of the edge signal of the 5G macro base station.

Proposition 1: Assume that the maximum number of iteration in Step A4, B4, and C7 is T. The computational complexity of the overall procedure from Step 1 to Step 5 is $O\left(mTN_D S_1 S_2\right)$.

Sketch of proof. To analyze the computational complexity, it can be determined via analyzing the worst running time of the overall procedure from Step 1 to Step 5. For Step 3, we can determine the running time is $O\left(mTN_D S_1^2\right)$. Next, it can be derived that the running time of Step 4 is $O\left(TN_D S_1\right)$. Furthermore, for Step 5, it can be derived that there is a running time of $O\left(\left(N_D+S_1 S_2\right) T\right)$. Since $S_1 < S_2$, it can be obtained that the overall running time for the procedure of our approach is $O\left(mTN_D S_1 S_2\right)$.

V. NUMERICAL RESULTS

In this section, we demonstrate the proposed approach through solving a series of numerical examples. Several cases are solved in the computational experiments to locate the macro and micro base stations under different budget condition. A cost-benefit analysis of the number of macro and micro base stations is also conducted to determine the optimal deployment plan.

A. PARAMETER SETTINGS

The parameter settings of the experimental example are given as follows. For the macro base station, the coverage radius is $A_1 = 1,500$ meters, and the unit price P_1 is RMB 1,300,000. For the micro base station, the coverage radius is $A_2 = 400$ meters, and the unit price P_2 is RMB 200,000. In addition, the coverage area of a macro base station is around 1,100 to 1,500 meters. The maximum budget for all cases in this example is RMB 7 million. Randomly generate $N_D = 100$ demand points and their coordinates $\{(X_1, Y_1), (X_2, Y_2), \ldots, (X_{99}, Y_{99}), (X_{100}, Y_{100})\}$ on a rectangular map. In Table 2, it shows these 100 coordinates of demand points. A preset threshold $R_c = 95\%$ is given for the minimum QoS requirement of the total signal coverage rate.

Our computational environment is run by means of MATLAB 2017a on Windows 10 Professional 64-bit with

TABLE 2. The coordinates of 100 demand points.

i	X_i	Y_i	i	X_i	Y_i
1	-446.92	274.96	26	-1750.73	-1299.94
2	-191.77	-1225.930	27	-887.71	-1782.76
3	-1892.96	816.95	28	-361.48	-927.17
4	-298.85	606.32	29	507.24	184.04
5	-1576.78	-672.41	30	1676.41	1100.75
6	-1827.55	86.27	31	-339.39	415.04
7	224.49	-1900.95	32	846.00	-735.62
8	445.15	-1910.91	33	1883.50	-266.59
9	955.33	1194.10	34	-258.12	1371.12
10	-972.32	-1568.75	35	541.53	504.53
11	905.04	755.23	36	1606.22	-909.81
12	853.01	1100.10	37	1486.33	58.14
13	15.06	1165.98	38	-1429.14	1553.60
14	1571.08	837.88	39	-1197.61	-1302.82
15	1117.54	1786.15	40	483.72	1280.27
16	-20.56	-807.92	41	1100.12	-1275.23
17	1046.03	1983.28	42	-1012.76	-1610.95
18	668.18	217.79	43	-522.19	-1874.74
19	1912.45	624.35	44	-635.61	-1959.30
20	-1531.72	1781.40	45	-174.44	1869.79
21	1477.29	-1101.45	46	-1316.71	1552.15
22	271.42	1926.07	47	982.42	-1801.29
23	-1519.39	-1317.51	48	-1608.09	680.83
24	1881.32	1764.24	49	1561.08	1906.49
25	1359.87	1827.84	50	-1671.62	-1118.94
	X_i	Y_i	i	X_i	Y_i
51	1126.09	-1663.77	76	900.99	1795.53
52	1394.71	-564.54	77	-330.48	-1456.99
53	-196.49	932.73	78	-907.32	46.06
54	421.30	408.58	79	-741.17	-1834.27
55	-582.12	-194.52	80	326.78	-750.36
56	1036.38	1651.21	81	757.43	-712.92
57	357.76	-1987.29	82	1455.47	1793.29
58	446.28	40.32	83	-1156.57	-1170.64
59	1372.68	-1422.15	84	27.01	-42.63
60	-172.05	18.60	85	-299.80	-221.30
61	1531.16	272.86	86	-1041.20	1283.40
62	-25.71	568.68	87	1030.09	-1930.08

TABLE 2. *(Continued.)* The coordinates of 100 demand points.

63	491.40	-1172.26	88	1167.65	1154.06
64	248.66	-639.25	89	-456.48	163.16
65	886.64	-690.10	90	-727.78	-1818.09
66	187.08	459.86	91	-76.30	55.40
67	1137.76	364.76	92	-885.98	-217.50
68	-214.59	751.70	93	-1367.86	-34.54
69	1647.63	-1334.25	94	-418.37	639.56
70	-1653.65	608.91	95	-858.18	21.48
71	1995.75	1074.55	96	-1027.80	967.44
72	910.32	-416.93	97	570.08	1775.40
73	233.63	-414.94	98	1827.70	1197.30
74	-1428.70	768.48	99	-1254.66	-249.09
75	1350.55	-1049.31	100	1638.07	-1638.75

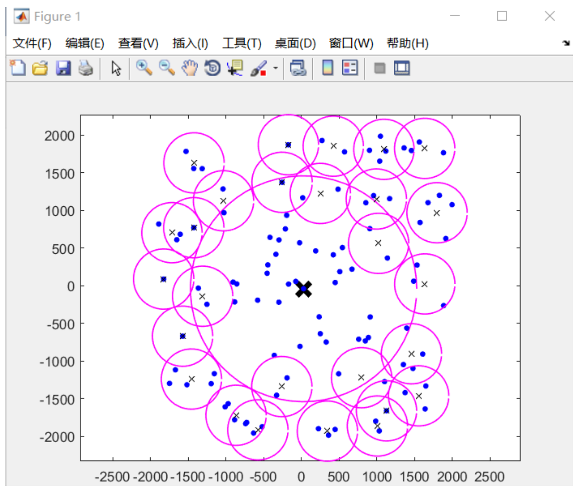

FIGURE 1. The initial coverage map for the location of one macro base station and twenty seven micro base stations in Case I.

the processor Intel (R) Core (TM) i7-6500U CPU@2.50GHz dual-core and 8 GB memory.

B. SOLUTION CASE I

In the first case, we set the number of macro base stations as as $S_1 = 1$. Through Steps A1-A4 in the implementation procedure of our approach, we can determine the location coordinate of this macro base station, which is $(27.00, -42.63)$. Then, through the procedure, it outputs 69 boundary points and noise points. Next, we apply Steps B1-B4 in the implementation procedure of our approach to determine the initial coordinates of 27 micro base stations, which are listed in Table 3.

It can be seen from Fig. 1 the initial coverage map for the location of 1 macro base station and 27 micro base stations. Although all the demand points are completely covered, but

TABLE 3. The initial coordinates of twenty seven micro base stations in scheme I.

Index Number	The Initial Coordinate	Index Number	The Initial Coordinate
1	(1021.40, 559.99)	15	(-1827.55, 86.27)
2	(-1459.19, -1241.97)	16	(249.39, 1223.12)
3	(1006.26, -1865.67)	17	(-1311.26, -141.82)
4	(-1428.70, 768.48)	18	(-868.35, -1722.97)
5	(-578.90, -1917.02)	19	(342.47, -1933.05)
6	(1457.19, -906.28)	20	(-1034.50, 1125.42)
7	(-1576.78, -672.41)	21	(1632.62, 1821.34)
8	(1796.68, 966.97)	22	(795.76, -1223.75)
9	(-174.44, 1869.79)	23	(-1718.23, 702.23)
10	(1092.16, 1808.80)	24	(1126.09, -1663.77)
11	(420.75, 1850.74)	25	(-258.11, 1371.12)
12	(1633.66, 21.47)	26	(992.00, 1149.42)
13	(-1425.85, 1629.05)	27	(-261.13, -1341.46)
14	(1552.79, -1465.05)		

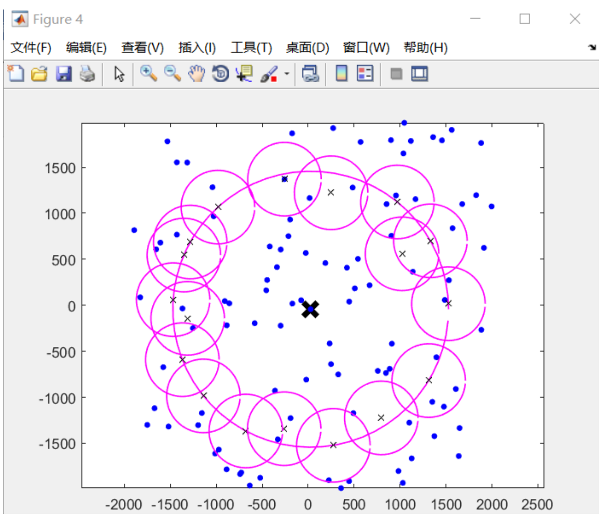

FIGURE 2. The final coverage map for the determined location of one macro base station and eighteen micro base stations in Case I.

the number of micro base stations required is too large to meet the goal of economic benefits. Therefore, we continue to implement Steps C1-C7 to achieve the goal for cost minimization, i.e., the objective function (1).

We can fine-tune or delete the coordinates of the initial micro base stations through Steps C1-C7 for the situation where those special micro base stations are outside the coverage of macro base station. In Fig. 2, it illustrates the final location of 1 macro base station and 18 micro base stations determined from our approach. It is found that the number of uncovered demand points is 37, and the signal coverage rate is computed as 63%. Besides, the required deployment cost for Scheme I is RMB 4,900,000. In Table 4, it summarizes the final coordinates of 18 micro base stations, the number of uncovered points, the signal coverage rate and the required cost of scheme I.

TABLE 4. The final coordinates of eighteen micro base stations, number of uncovered points, signal coverage rate and the required cost of scheme I.

The Final Coordinate of Micro Base Station No. 1	(1021.40, 559.99)
The Final Coordinate of Micro Base Station No. 2	(249.39, 1223.12)
The Final Coordinate of Micro Base Station No. 3	(-1311.26, -141.82)
The Final Coordinate of Micro Base Station No. 4	(795.76, -1223.75)
The Final Coordinate of Micro Base Station No. 5	(-258.12, 1371.12)
The Final Coordinate of Micro Base Station No. 6	(-261.13, -1341.46)
The Final Coordinate of Micro Base Station No. 7	(-1140.31, -984.64)
The Final Coordinate of Micro Base Station No. 8	(-1283.32, 687.47)
The Final Coordinate of Micro Base Station No. 9	(1311.05, -818.02)
The Final Coordinate of Micro Base Station No. 10	(-1369.20, -590.90)
The Final Coordinate of Micro Base Station No. 11	(1329.89, 700.67)
The Final Coordinate of Micro Base Station No. 12	(1525.81, 17.17)
The Final Coordinate of Micro Base Station No. 13	(-1469.38, 61.38)
The Final Coordinate of Micro Base Station No. 14	(-678.37, -1366.43)
The Final Coordinate of Micro Base Station No. 15	(273.90, -1522.17)
The Final Coordinate of Micro Base Station No. 16	(-981.82, 1067.45)
The Final Coordinate of Micro Base Station No. 17	(-1352.60, 546.18)
The Final Coordinate of Micro Base Station No. 18	(970.80, 1123.24)
Number of Uncovered Demand Points	37
Signal Coverage Rate	63%
Required Cost (RMB)	4,900,000

C. SOLUTION CASE II

In the second case, the number of macro base stations is given as $S_1 = 2$. By implementing Steps A1-A4, we can determine the location coordinates of 2 macro base stations,

TABLE 5. The initial coordinates of twenty micro base stations in scheme II.

Index Number	The Initial Coordinate	Index Number	The Initial Coordinate
1	(1063.89, -557.19)	11	(-1645.85, 718.79)
2	(-635.61, -1959.30)	12	(-1647.25, -1245.46)
3	(-174.44, 1869.79)	13	(1642.85, -1486.50)
4	(-1425.85, 1629.05)	14	(-1483.36, -65.79)
5	(-667.22, 126.42)	15	(1478.02, -1020.19)
6	(1046.20, -1798.37)	16	(-1034.50, 1125.42)
7	(1833.29, 1124.20)	17	(1912.45, 624.35)
8	(401.46, -1949.10)	18	(1881.32, 1764.24)
9	(1355.61, 1877.72)	19	(1236.40, -1348.69)
10	(1633.66, 21.47)	20	(-1576.78, -672.41)

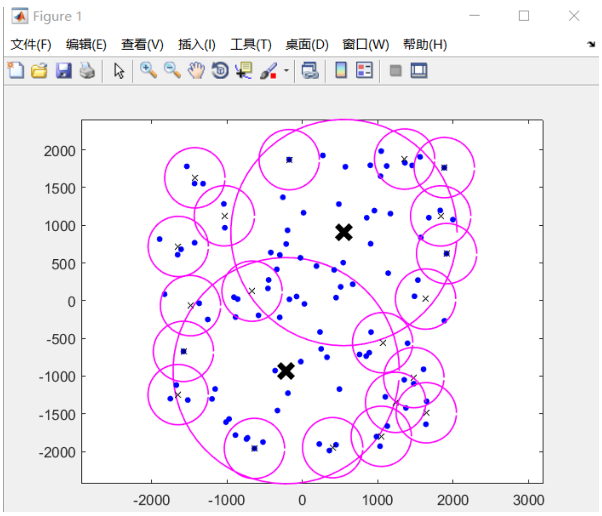

FIGURE 3. The initial coverage map for the location of two macro base stations and twenty micro base stations in Case II.

which are (551.19, 902.92) and (−214.72, −928.13). Next, through the procedure, it outputs 49 boundary points and noise points. Then we apply Steps B1-B4 to determine the initial coordinates of 20 micro base stations, which are summarized in Table 5. To achieve the goal for cost minimization, we continue to implement Steps C1-C7. In Fig. 3, it shows the initial coverage map for the location of 2 macro base stations and 20 micro base stations.

For those initial micro base stations outside the coverage of macro base stations, we can adjust their coordinates or delete them through Steps C1-C7. It is illustrated in Fig. 4 the final location of those 2 macro base stations and 17 micro base stations determined from our approach. It is observed that

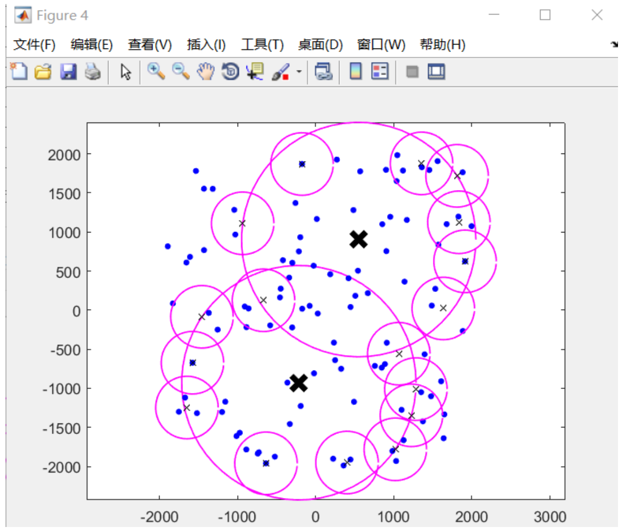

FIGURE 4. The final coverage map for the determined location of two macro base stations and twenty micro base stations in Case II.

the number of uncovered demand points is 10, and the signal coverage rate is computed as 90%. Meanwhile, the required deployment cost for Scheme II is RMB 6,000,000. In Table 6, it shows the final coordinates of 17 micro base stations, the number of uncovered points, the signal coverage rate and the required cost of scheme II.

D. SOLUTION CASE III

In the third case, the number of macro base stations is set as $S_1 = 3$. In Table 7, it shows the location coordinates of 3 macro base stations after implementing Steps A1-A4. Next, it outputs the number of boundary points and noise points is 28 and their coordinates. It can be observed from Table 8, we can determine the initial coordinates of 11 micro base stations by applying Steps B1-B4 in the procedure. For the situation where the initial micro base station is outside the coverage of a macro base station, we fine-tune these special coordinates through Steps C1-C7.

It is observed from Fig. 5 that the final location of 3 macro base stations and 11 micro base stations can be determined from our approach. In this scheme, the number of uncovered demand points is zero, and the signal coverage rate is 100%. In addition, the required deployment cost for Scheme III is RMB 6,100,000. In Table 9, it shows the final coordinates of 11 micro base stations, the number of uncovered points, the signal coverage rate and the required cost of scheme III.

E. SOLUTION CASE IV

In the fourth case, the number of macro base stations is given as $S_1 = 4$. By implementing Steps A1-A4, we can determine the location coordinates of 4 macro base stations, which are listed in Table 10. Next, through the procedure, it outputs the number of boundary points and noise points is 14 and their coordinates. By applying Steps B1-B4, we can determine the initial coordinates of 6 micro base stations. Because there is

TABLE 6. The final coordinates of seventeen micro base stations, number of uncovered points, signal coverage rate and the required cost of scheme II.

The Final Coordinate of Micro Base Station No. 1	(1063.89, -557.19)
The Final Coordinate of Micro Base Station No. 2	(-635.61, -1959.30)
The Final Coordinate of Micro Base Station No. 3	(-174.44, 1869.79)
The Final Coordinate of Micro Base Station No. 4	(-667.22, 126.42)
The Final Coordinate of Micro Base Station No. 5	(1833.29, 1124.20)
The Final Coordinate of Micro Base Station No. 6	(401.46, -1949.10)
The Final Coordinate of Micro Base Station No. 7	(1355.61, 1877.72)
The Final Coordinate of Micro Base Station No. 8	(1633.66, 21.47)
The Final Coordinate of Micro Base Station No. 9	(-1647.25, -1245.46)
The Final Coordinate of Micro Base Station No. 10	(1912.45, 624.35)
The Final Coordinate of Micro Base Station No. 11	(-1576.78, -672.41)
The Final Coordinate of Micro Base Station No. 12	(1019.81, -1780.15)
The Final Coordinate of Micro Base Station No. 13	(-1455.26, -84.89)
The Final Coordinate of Micro Base Station No. 14	(1283.07, -1009.59)
The Final Coordinate of Micro Base Station No. 15	(-934.26, 1111.35)
The Final Coordinate of Micro Base Station No. 16	(1810.27, 1718.23)
The Final Coordinate of Micro Base Station No. 17	(1225.99, -1345.68)
Number of Uncovered Demand Points	10
Signal Coverage Rate	90%
Required Cost (RMB)	6,000,000

TABLE 7. The coordinates of three macro base stations in scheme III.

The Coordinate of Macro Base Station No. 1	(472.40, -1212.56)
The Coordinate of Macro Base Station No. 2	(-847.01, 189.46)
The Coordinate of Macro Base Station No. 3	(1053.45, 1197.73)

no micro base station outside the coverage of the macro base stations, there is no need to adjust the location of these four micro base stations.

It is illustrated in Fig. 6 that the final location of 4 macro base stations and 6 micro base stations are determined from the proposed approach. It is found that the number of uncovered points is zero, and the signal coverage rate is computed as 100%. Meanwhile, the required deployment cost for Scheme IV is RMB 6,400,000. In Table 11, it summarizes

TABLE 8. The initial coordinates of eleven micro base stations in scheme III.

Index Number	The Initial Coordinate	Index Number	The Initial Coordinate
1	(-1425.85, 1629.05)	7	(476.76, 112.18)
2	(1630.64, -1294.27)	8	(-1892.96, 816.95)
3	(-1084.81, -1413.29)	9	(-1647.25, -1245.46)
4	(1588.18, -257.66)	10	(-702.89, -1853.83)
5	(-216.28, 1620.45)	11	(-1041.20, 1283.39)
6	(-1576.78, -672.41)		

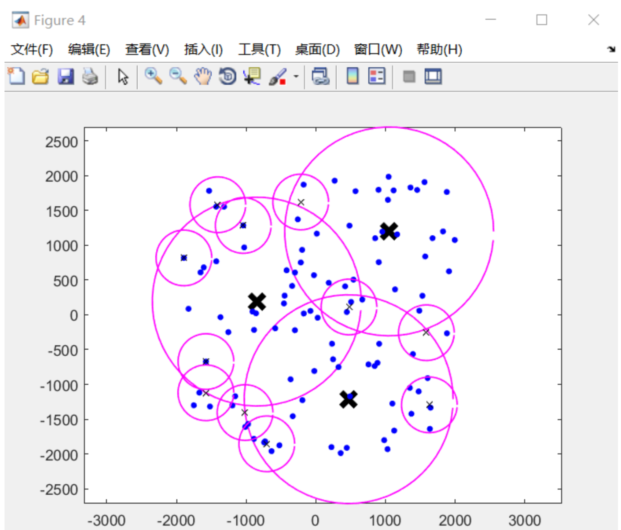

FIGURE 5. The final coverage map for the determined location of three macro base stations and eleven micro base stations in Case III.

the final coordinates of 6 micro base stations, the number of uncovered points, the signal coverage rate and the required cost of scheme IV.

F. SOLUTION CASE V

In the final case, the number of macro base stations is set as $S_1 = 5$. In Table 12, we summarize the location coordinates of 5 macro base stations by implementing Steps A1-A4. Next, through the procedure, it outputs the number of boundary points and noise points is 8 and their coordinates. Then we apply Steps B1-B4 to determine the initial coordinates of 4 micro base stations. Because there is no micro base station outside the coverage of the macro base stations, there is no need to adjust the location of these four micro base stations.

In Fig. 7, it shows the final location of 5 macro base stations and 4 micro base stations determined from our approach. In this scheme, there is zero uncovered demand point, thus the signal coverage rate is 100%. Meanwhile, the required deployment cost for Scheme V is RMB 7,300,000.

TABLE 9. The final coordinates of eleven micro base stations, number of uncovered points, signal coverage rate and the required cost of scheme III.

The Final Coordinate of Micro Base Station No. 1	(1630.64, -1294.27)
The Final Coordinate of Micro Base Station No. 2	(1588.18, -257.66)
The Final Coordinate of Micro Base Station No. 3	(-216.28, 1620.45)
The Final Coordinate of Micro Base Station No. 4	(-1576.78, -672.41)
The Final Coordinate of Micro Base Station No. 5	(476.76, 112.18)
The Final Coordinate of Micro Base Station No. 6	(-1892.96, 816.95)
The Final Coordinate of Micro Base Station No. 7	(-702.89, -1853.83)
The Final Coordinate of Micro Base Station No. 8	(-1041.20, 1283.39)
The Final Coordinate of Micro Base Station No. 9	(-1406.60, 1581.17)
The Final Coordinate of Micro Base Station No. 10	(-1015.29, -1404.33)
The Final Coordinate of Micro Base Station No. 11	(-1577.61, -1120.59)
Number of Uncovered Demand Points	0
Signal Coverage Rate	100%
Required Cost (RMB)	6,100,000

TABLE 10. The coordinates of four macro base stations in scheme IV.

The Coordinate of Macro Base Station No. 1	(-864.36, -1388.05)
The Coordinate of Macro Base Station No. 2	(1143.15, 1338.88)
The Coordinate of Macro Base Station No. 3	(-652.26, 539.29)
The Coordinate of Macro Base Station No. 4	(1042.61, -1010.70)

In Table 13, it shows the final coordinates of 4 micro base stations, the number of uncovered points, the signal coverage rate and the required cost of scheme V.

G. A COST-BENEFIT ANALYSIS

A total of 5 possible schemes are determined in the numerical experiments. The signal coverage rate and deployment cost of 5 cases are summarized in Table 14, respectively.

It can be seen from Table 14, the signal coverage rate increases when the total cost of building base stations increases. The required deployment cost of Schemes II to IV is almost the same. However, the unit increase in signal coverage from Scheme II to Scheme III is significantly greater than that from Scheme III to Scheme IV.

The target QoS requirement for the total signal coverage needs to meet a minimum threshold $R_c = 95\%$, so the first two schemes (Scheme I and Scheme II) are not feasible

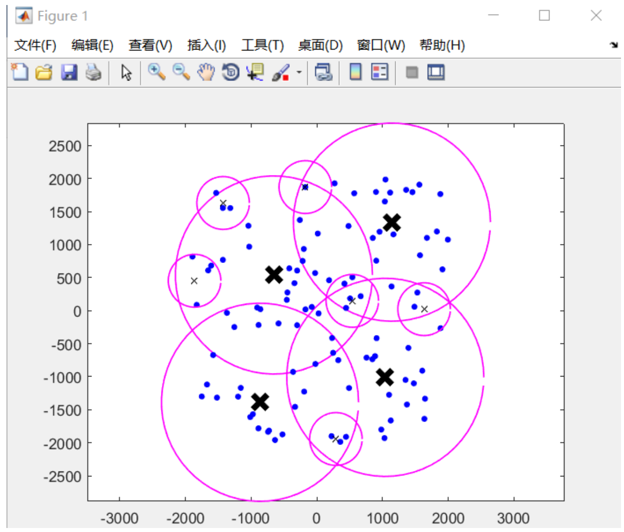

FIGURE 6. The final coverage map for the determined location of four macro base stations and six micro base stations in Case IV.

TABLE 11. The final coordinates of six micro base stations, number of uncovered points, signal coverage rate and the required cost of scheme IV.

The Final Coordinate of Micro Base Station No. 1	(-1860.26, 451.62)
The Final Coordinate of Micro Base Station No. 2	(1633.67, 21.47)
The Final Coordinate of Micro Base Station No. 3	(-174.44, 1869.79)
The Final Coordinate of Micro Base Station No. 4	(-1425.85, 1629.05)
The Final Coordinate of Micro Base Station No. 5	(291.13, -1944.12)
The Final Coordinate of Micro Base Station No. 6	(540.56, 147.39)
Number of Uncovered Demand Points	0
Signal Coverage Rate	100%
Required Cost (RMB)	6,400,000

TABLE 12. The coordinates of five macro base stations in scheme V.

The Coordinate of Macro Base Station No. 1	(-1327.80, 884.18)
The Coordinate of Macro Base Station No. 2	(1138.55, -1139.78)
The Coordinate of Macro Base Station No. 3	(-862.19, -1484.20)
The Coordinate of Macro Base Station No. 4	(1230.53, 1416.19)
The Coordinate of Macro Base Station No. 5	(-51.62, 256.83)

solutions. Under the total budget constraint of RMB 7 million, Scheme V is also infeasible.

The final feasible solutions determined from the implementation procedure of our approach are Scheme III and Scheme IV, and both Scheme III and Scheme IV can achieve

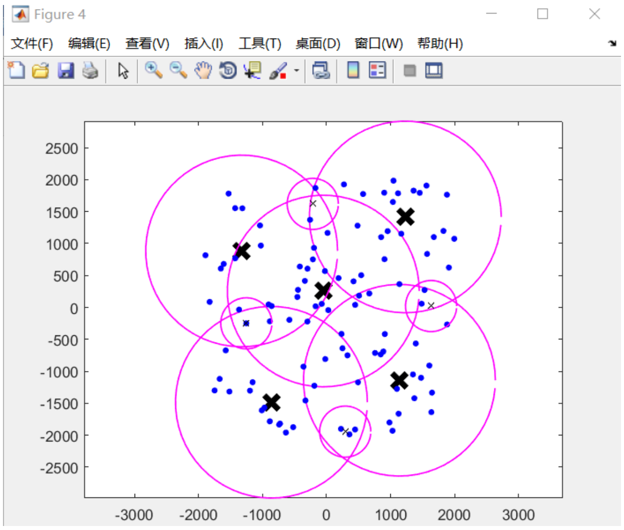

FIGURE 7. The final coverage map for the determined location of five macro base stations and four micro base stations in Case V.

TABLE 13. The final coordinates of four micro base stations, number of uncovered points, signal coverage rate and the required cost of scheme V.

The Final Coordinate of Micro Base Station No. 1	(1633.66, 21.47)
The Final Coordinate of Micro Base Station No. 2	(-1254.66, -249.09)
The Final Coordinate of Micro Base Station No. 3	(291.13, -1944.12)
The Final Coordinate of Micro Base Station No. 4	(-216.28, 1620.45)
Number of Uncovered Demand Points	0
Signal Coverage Rate	100%
Required Cost (RMB)	7,300,000

TABLE 14. Numerical results of five schemes.

Scheme	Number of Macro Base Stations, S_1	Number of Micro Base Stations, S_2	Signal Coverage Rate, D_M/N_D	Required Cost (RMB), $P_1 \cdot S_1 + P_2 \cdot S_2$
I	1	18	63%	4,900,000
II	2	17	90%	6,000,000
III	3	11	100%	6,100,000
IV	4	6	100%	6,400,000
V	5	4	100%	7,300,000

100% signal coverage rate. It is concluded that Scheme III is the optimal solution because the deployment cost of Scheme III is less than the required cost of Scheme IV. From the performance evaluation in this section, it is shown that the proposed coverage-based location approach can be effectively applied in the deployment of 5G base stations.

VI. CONCLUSION

In this paper, an executable approach for the deployment of 5G base stations is presented under balancing both the budget and signal coverage. A mixed-integer nonlinear optimization model with two objective functions is formulated and solved in the present work for the site selection and location of 5G macro and micro base stations. The proposed coverage-based location approach can achieve the minimum of deployment cost and the maximum of signal coverage rate in a balanced manner.

Moreover, a series of numerical examples have been solved in the paper to demonstrate the proposed coverage-based location approach. In addition, a cost-benefit analysis has also been conducted to determine the optimal deployment plan for the number of macro and micro base stations, which can optimally reduce the deployment cost and strengthen the signal coverage. It is concluded that we presented an implementation procedure for the cooperative operation and deployment scheme for optimizing the location of 5G heterogeneous base stations. The main contribution of the present work is the formulation of the deployment of 5G heterogeneous base stations as an optimization model. Besides, an executable procedure of the proposed coverage-based location approach is contributed for solving the studied optimization problem.

The application of our research work could be used in the deployment of 5G heterogeneous base stations. For example, in coverage-oriented deployments, the designers could apply the analytical methods from determinantal point processes and stochastic geometry to maintain a certain minimum separation between neighboring base stations. Discussions and certain measures, such as coverage probability and propagation effects, on the idea of modeling base station locations by point processes for real-world macrotier deployments can be found in the reference [38]. Another possible applications and challenges associated with our modeling of base station deployment can be found in the reference [39], such as energy efficiency, user support, and adaptive multimedia services for the next generation mobile networks.

Furthermore, the cost-benefit analysis proposed in the present paper could also be helpful for the telecom operators when considering the investment of China's new infrastructure. The MIIT of the People's Republic of China estimates that the telecom operators in China are going to build at least 680,000 base stations in one year. In the evolution of mobile communications, China has successively experienced three stages of tracking 2G, breakthrough of 3G, and synchronization for 4G. China has already launched commercial deployment of 5G networks and participated in the planning of 5G networks to gain advantages in the global 5G industry chain. In the next decades, the countries that dominate 5G technology and applications will possess economic, political, and military advantages.

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