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Location Selection Scheme of Smart Light Pole Based on Segmentation Optimization

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Abstract

Smart lamp poles, as a key component of smart cities, not only meet the lighting demands but also provide an ideal deployment platform for 5G micro-base stations and charging piles. Therefore, the site selection of smart lamp poles is of great importance, as it needs to consider the relationships between various subsystems, such as 5G micro-base stations and charging piles, while achieving high efficiency, wide coverage, and low cost. Based on this, this paper proposes an innovative optimization model for smart lamp pole site selection. The model starts from a planar perspective, using a segmented optimization strategy to pre-screen the candidate points, and then employs a genetic algorithm to optimize the solutions, ensuring the efficiency and practicality of the site selection scheme. After adjusting the grid parameters, the model is validated through simulations in a specific region, successfully providing a comprehensive and practical smart lamp pole site selection scheme. This study provides a valuable reference for the rational deployment of smart lamp poles in smart city construction.

Keywords

Segmentation optimization; Smart lamp pole; Genetic algorithm; 5G micro-base station; Charging pile

1. Introduction

In the part of "accelerating the construction of a new development pattern and promoting high-quality development", a report to the 20th CPC National Congress of the Communist Party of China proposed to speed up the construction of a manufacturing power, a quality power, a space power, a transportation power, a network power and a digital China. As an important carrier for the construction of "network power" and "transportation power", a smart light pole is also an important part of a smart city. It not only improves the intelligence and information level of urban lighting management, but also saves energy and reduces operation and maintenance costs to a certain extent [1]. However, there are still many problems on many urban roads, such as an excessive number of poles, mutual influence of installation, difficult maintenance, and line leakage. Based on this, the integration of the concept of smart development and overall consideration of urban information level, comprehensive competitiveness, green and low-carbon, humanistic technology, and other factors, the construction and popularization of smart light poles is urgent [2].

Song Li used a genetic algorithm to conduct research and analysis on-site optimization, modeled the site selection of base stations, and determined three optimization objective functions [3]. Chang Hao et al. proposed to use the "A-star algorithm" to search for the optimal path, and then determine the optimal layout area of the charging pile according to the intersection points [4]. Li Wenchao et al. proposed a quantifiable index to measure the degree of system integration and established a 5G micro-base station location model based on the perspective of multi-system integration [5, 6]. Bao Lixia et al. analyzed the planning of fast charging piles based on the road network structure and the uneven distribution of charging demand [7].

Based on the sub-system 5G microbase station and charging pile on the smart light pole [3], this paper will comprehensively locate and optimize the layout of the multi-functional smart light pole system from multiple perspectives, so as to better serve the construction of smart cities.

2. Location Model of 5G Micro-base Station and Charging Pile of Light Pole Subsystem

2.1 Location of 5G Microbase Stations on the Plane

The multi-functional light pole system is a natural platform for 5G micro-base stations. The reasonable site selection scheme shall comply with the following basic conditions [3]:

(1) High coverage principle: The coverage range of 5G micro-base stations is about 200m. It is related to the hanging height and frequency band. 5G micro base station with macro base station to achieve high coverage of 5G signal in the region;

(2) Low-cost principle: Considering the total cost, the total cost is required to be as low as possible, then the number of 5G micro-base stations should be as small as possible;

(3) The principle of efficient utilization: the base station signal should be covered in the populated area as far as possible, and the construction of the base station should be reduced in the unmanned area;

(4) Principle of low overlap rate: the signal coverage between different micro-base stations may overlap, and the overlap area should be reduced as much as possible to reduce the overlap rate.

Firstly, the location problem of the 5G microbase station on a simple plane road is considered. In order to meet the four conditions mentioned above, this paper takes the smart light pole as the center of the circle and defines the coverage radius of 5G microbase station signal as r; On the same line, the signal coverage area between two different light poles has two intersection points, and the clip Angle between the line segment from the center of each smart light pole to one of the intersection points and the line where the light pole is located is θ_i; The overlap length of the signal on the straight line between the two smart light poles is $x = 2r(1 - cos\theta_i)$; The overlap rate of each light pole is defined as μ_i, indicating the ratio of the overlap area to the total area covered by the signal, generally less than 15%; Define the length of the line where the light pole is located as L; Define the signal coverage as η, in order to achieve a higher signal coverage, usually the coverage should be more than 90%; The number of light poles is n.

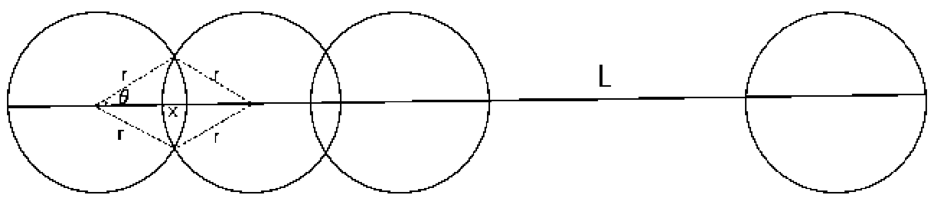

Figure 1. **5G microbase station layout on a straight road.**

The area of the overlap on the line is $2(\theta_i r^2 - r^2\ sin\theta_i\ cos\theta_i)$, so the expression for the overlap rate on the line is

$$\mu = \frac{\sum_1^{n-1}(2\frac{2\theta_i}{2\pi}\pi r^2 - r^2 sin2\theta_i)}{n\pi r^2 - \sum_1^{n-1}(2\frac{2\theta_i}{2\pi}\pi r^2 - r^2 sin2\theta_i)} = \frac{\sum_1^{n-1}(2\theta_i - sin2\theta_i)}{n\pi r^2 - \sum_1^{n-1}(2\theta_i - sin2\theta_i)}. \quad (1)$$

The relationship between the number of light poles n and the length of the line L is

$$\eta L \leq (n-1)(2r - x) + x \quad (2)$$

Hence, we have

$$n \geq \frac{\eta L - 2x + 2r}{2r - x}. \quad (3)$$

This is the expression for the number of light poles n on the line.

The situation on the plane is slightly more complicated than the situation on the straight line, taking the rectangular area as an example, the rectangle can be divided into several straight lines, and the light pole is distributed on each line. In order to ensure that the signal of the lamp pole can cover the rectangular area as much as possible, the length of the signal of the lamp pole falling outside the area should be $d \leq r - rsin\theta_i$. Suppose the rectangle has a horizontal length of M and a vertical width of N.

If the line is divided in the horizontal direction, it can be found in the horizontal direction

$$\eta M \leq (n_i - 1)(2r - x) + x. \tag{5}$$

The vertical direction is

$$\eta N \leq (n_j - 1)(2r - x) + (2r - d - x) = 2n_j r - n_j x - 2r + x + 2r - d - x = n_j(2r - x) - d,$$

where n_i and n_j are the number of light poles in the horizontal and vertical directions, respectively, i.e

$$n_i \geq \frac{\eta M - 2x + 2r}{2r - x}, n_j \geq \frac{\eta N + 2d}{2r - x}. \tag{6}$$

The number of light poles in the rectangular area is:

$$n = n_i n_j \geq \frac{\eta M - 2x + 2r}{2r - x}\frac{\eta N + 2d}{2r - x} = \frac{(\eta M - 2x + 2r)(\eta N + 2d)}{(2r - x)^2}. \tag{7}$$

In summary, a linear programming model can be constructed, and the objective function is as follows:

$$n = min\left\{\frac{(\eta M - 2x + 2r)(\eta N + 2d)}{(2r - x)^2}\right\}. \tag{8}$$

The meaning is to take cost as an optimization target, that is, the number of 5G microbase stations to be built. The constraints are as follows:

$$s.t.\begin{cases} \eta M \leq (n_i - 1)(2r - x) + x \\ \eta N \leq n_j(2r - x) - d \\ x = r - (2rcos\theta_i - r) \\ d \leq r - rsin\theta_i \\ \frac{\sum_1^{n-1}(2\theta_i - sin2\theta_i)}{n\pi r^2 - \sum_1^{n-1}(2\theta_i - sin2\theta_i)} \leq 10\% \\ \eta \geq 90\% \end{cases}. \tag{9}$$

The objective is to ensure comprehensive 5G micro-base station coverage, with a target coverage rate exceeding 90% across the entire area. Additionally, the signal overlap rate should be limited to 10% or less, while the signal spillage outside the designated area, i.e., in unserved zones, should be minimized.

2.2 Location of Charging Piles on the Plane

The multifunctional lamp post subsystem charging pile can meet the charging demand of new energy vehicles. The reasonable site selection scheme should follow the following basic conditions [5]:

(1) Geographical principle: The location of charging piles must be located in a suitable geographical position, so as to provide users with portable charging services, and more charging piles should be built in places with large population.

(2) Low-cost principle: Considering the total cost, the total cost is required to be as low as possible, and the number of charging piles should be as small as possible.

(3) The principle of convenient transportation: In order not to affect the traffic, the location of the charging pile should be a certain distance from the traffic intersection.

(4) Principle of optimal range: The distance from different users to the charging pile should be within an appropriate range. After the location model of 5G micro-base stations is determined by analytic geometry, the location positions of all 5G micro-base stations are taken as candidate points v_i. The cost of each candidate point is C_i. d_{ij} represents the distance between the candidate point argument v_i and the candidate point argument v_j. The population density is recorded as ρ. When ρ is greater than a certain threshold ρ_1, the number n of light poles should tend to the maximum value n_{max} and be greater than n_{max}, when necessary. When ρ is less than ρ_2, the number n of light poles should tend to the minimum value n_{min} and be greater than n_{min} when necessary. The distance between the light pole and the intersection is d_{io}, which should be greater than d_1. The distance between the light pole and the user is d_{ik}, which should be less than d_2. Let

$\tau \in \{0,1\}$ be a binary variable that indicates whether a candidate point is selected or not, where: $\tau = 1$ if the candidate point is selected, and $\tau = 0$ if the candidate point is not selected.

To sum up, a linear programming model can be constructed, with the objective function formulated as:

$$C = min \sum v_i \tau C_i, \tag{10}$$

where the objective C is to minimize the total cost. Constraints are as follows:

$$s.t. \begin{cases} n_{min} \le n \le n_{max} \\ \rho_1 \le \rho \le \rho_2 \\ d_{io} \ge d_1 \\ d_{ik} \le d_2 \end{cases}, \tag{11}$$

where the population density $\rho_1 \le \rho \le \rho_2$, the number of lamp poles is $n_{min} \le n \le n_{max}$. The distance between the light pole and the intersection should be d_{io} or greater than d_1. The distance between the light pole and the user should be d_{ik} and less than or equal to d_2.

2.3 Model Simulation Test

We select Area A of a certain location for the study of smart light pole placement. Firstly, the location of the 5G micro-base station is selected by subsection optimization [8]. The road in the map divides area A into several small areas, namely A_1, A_2, A_3 as shown in Figure 2.

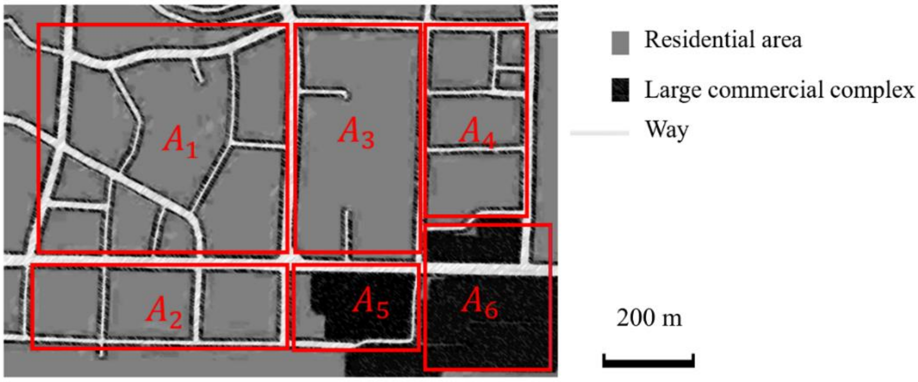

Figure 2. Division of a region.

Apply the above model to each small area A_i and solve it. For the convenience of calculation, each θ_i is defined as a unified value $\frac{\pi}{6}$. Take one area as an example, and the relationship between the coverage rate of this area and the number of light poles is shown in Table 1.

Table 1. Calculation results by region

Region name	Area (square kilometers)	Coverage (%)	Overlapping rate (%)	Number of lampposts (units)
A_1	0.29	93.8	5.5	12
A_2	0.11	91.7	4.5	4
A_3	0.14	94.4	6.1	9
A_4	0.12	92.1	5.0	6
A_5	0.05	98.4	6.1	3
A_6	0.09	99.1	5.0	6

At this time, each light pole preliminarily selected is taken as a "candidate point", that is, a total of 40 candidate points, and the location of the charging pile is selected. Using a genetic algorithm to realize the location selection scheme of a multifunctional light pole system, it is necessary to regard the position of each light pole as a "gene" and the position of all light poles as a "chromosome". Through crossover, mutation, and other operations, new chromosomes are constantly generated, and chromosomes with higher adaptability are screened out, and finally, the best site selection scheme is obtained.

(1) Defining constants: defining the number of candidate points as 40, and giving the coordinates of each candidate point; The number of intersections is 36, and the coordinates of each intersection are given; The number of iterations of the algorithm is 100, the initial population size is 50, and the mutation rate is 0.1. Define the cost of each candidate point.

(2) Objective function: the objective function is to calculate the total cost of a given solution. For each candidate point, multiply its cost by the binary value of whether to select the candidate point and add all the results to get the total cost.

(3) Define the constraint conditions: the number constraint of light poles; Population density constraint; and Distance constraint.

(4) Initializing population: randomly generating some solutions as the initial population. Each solution is a binary vector of length NUM_CANDIDATES, indicating whether each candidate point is selected or not. The initial population size is POPULATION_SIZE.

(5) Performing iterative evolution: calculating fitness; Cross; Variation; and Update population.

(6) Calculating the optimal solution: After several rounds of iterative evolution, the final population is obtained. Find the optimal solution, that is, the solution with the minimum objective function value [9].

Update the parameters and the optimal solution through the grid parameters, and finally output the optimal solution as follows: 30 candidate points are selected, as shown in Figures 3 and 4:

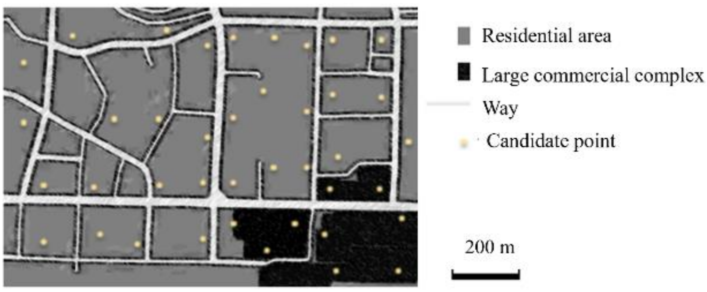

Figure 3. Lamp pole candidate point.

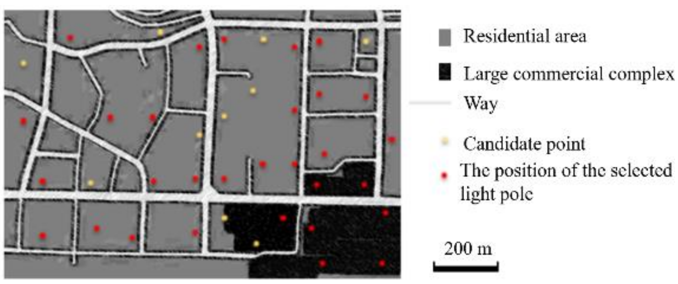

Figure 4. Selected Lamp pole point.

After the population is initialized, iteration is performed. Each generation selects the next generation population and then carries out crossover and mutation operations to generate the next generation population. Finally, the optimal individual and the corresponding cost are returned. By constantly evolving the individuals in the population, the individuals with the highest fitness were found, and finally 30 of the 40 candidate points in area A were selected as the landing position of the smart lamppost.

However, only 30 candidate points are selected, which can't meet the principle of high coverage. In order to meet the coverage rate of more than 90%, the candidate points should be adjusted. Here, the sequential least squares programming (SLSQP) algorithm can find the optimal solution of minimizing the objective function, that is, the candidate points that meet the constraints through repeated iterations. Finally, the position of the smart light pole in area A is shown in the table [10].

Table 2. The coordinates of the optimized smart light pole

Lamppost	Coordinate	Lamppost	Coordinate	Lamppost	Coordinate	Lamppost	Coordinate
lamppost 1	(4.69,1.28)	lamppost 11	(11.60,7.42)	lamppost 21	(12.49,5.26)	lamppost 31	(3.35,3.90)
lamppost 2	(8.38,6.86)	lamppost 12	(0.50,0.72)	lamppost 22	(15.00,14.56)	lamppost 32	(2.75,2.73)
lamppost 3	(0.01,10.19)	lamppost 13	(5.99,8.26)	lamppost 23	(1.99,13.12)	lamppost 33	(11.52,12.69)
lamppost 4	(2.47,0.09)	lamppost 14	(6.73,1.29)	lamppost 24	(4.60,8.10)	lamppost 34	(9.65,11.00)
lamppost 5	(2.60,6.34)	lamppost 15	(14.88,1.88)	lamppost 25	(15.00,14.56)	lamppost 35	(4.43,11.95)
lamppost 6	(6.13,4.32)	lamppost 16	(13.74,14.57)	lamppost 26	(1.99,11.31)	lamppost 36	(6.22,2.72)
lamppost 7	(4.51,14.61)	lamppost 17	(0.42,1.60)	lamppost 27	(13.26,1.05)	lamppost 37	(13.37,7.99)
lamppost 8	(1.77,9.81)	lamppost 18	(13.97,8.18)	lamppost 28	(14.21,12.92)	lamppost 38	(4.02,9.11)
lamppost 9	(1.27,2.05)	lamppost 19	(11.21,14.21)	lamppost 29	(9.77,0.53)	lamppost 39	(13.69,6.86)
lamppost 10	(2.90,14.04)	lamppost 20	(3.16,1.02)	lamppost 30	(7.52,2.04)	lamppost 40	(9.19,14.21)

At this time, the coverage rate of the light pole signal is 92.16%, and the overlap rate is 14.24%, all of which meet the principle of smart light pole location.

3. Conclusion

In this paper, a location model of smart light pole is established, which comprehensively considers the subsystems of smart light pole: 5G micro-base station and charging pile for location. Firstly, the location model of a smart pole 5G micro-base station in a straight line is obtained by following the principles of high coverage, low cost, high efficiency, and low overlap rate, and this model is extended to the plane. Then, according to the principles of geography, low cost, convenient transportation, and optimal range, the location model of charging piles for smart light poles is established. In practical operation, the location of smart light poles often needs to be optimized according to the route layout and population density of the map. Through subsection optimization, the candidate points of smart light poles are preliminarily selected. In this paper, the genetic algorithm and SLSQP algorithm are combined to solve the location scheme of smart light poles, and the result is obtained through grid parameters. The model established in this paper considers the location of two subsystems of smart light poles at the same time, which is efficient and practical.

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