Evaluating the Coverage of 5G Signals: Coupling Spatial Autocorrelation and 3D Sight Lines Based on GIS

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Abstract. 5G communication network has been developed and applied in recent years, the researches on 5G communication network planning have become gradually sufficient. However, the previous researches on the coverage planning of 5G signals are mostly based on 2D spatial framework, for the constructed 5G communication network, there is still a research gap in the evaluation of the coverage of 5G signals in outdoor environment of modern cities from the perspective of 3D spatial framework. We selected several blocks from Shenzhen city as the study area. In this study, we conducted spatial autocorrelation analysis on the spatial distribution of 5G base stations in the study area, and found that the characteristic of the spatial distribution of 5G BSs illustrates a kind of random rather than aggregate or discrete. And, we established a 3D model of the buildings and 5G BSs distribution in the study area, combined with the height of the buildings and the construction height of the 5G BSs, the 3D sight lines of the 5G BSs to the road network represents the LOS service coverage of the 5G BSs to the road network. The value of the Global Moran's I approaches to 0, the coverage ratio of the roads in the study area is about 18.89%.

Keywords: 5G · GIS · Spatial autocorrelation · 3D sight lines

1 Introduction

To meet the demand of mobile communication network in the rapidly development of economy and science, fifth-generation mobile communication technology (5G) has been developed and applied in recent years. 5G, which with the characteristics of enhanced mobile broadband (eMBB), massive machine type of communication (mMTC), ultra-reliable and low latency communications (URLLC), can be widely applied in Internet of Things (IoT), artificial intelligence (AI), virtual reality (VR) and self-driving cars [1, 2]. 5G unmanned vehicles will be one of the most valuable application scenarios, which can provide safer and more efficient transportation services [3]. The coverage of 5G signals

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to road networks in modern cities directly affects the realization of unmanned vehicles, meanwhile, it would characterize the coverage of 5G signals to urban outdoor area to a certain extent.

A high-frequency millimeter wave was adopted in 5G communication technology as a basic wireless network technology, which with the characteristic of huge amount of data carriage but over a short distance [4], so the effective coverage radius of most 5G base stations (BSs) are between 100 and 300 m [5, 6]. In modern cities, the high density of urban buildings limits the transmission of 5G signals, and building materials can almost isolate indoor and outdoor millimeter wave transmission signals [7], hence, in modern cities, densely buildings distribution is the main factor affecting the coverage of 5G signals, which will cause a penetration loss of 5G millimeter wave [8–10]. Attenuation of wireless communication signals during transmission is called the line-of-sight (LOS) effect [5, 11, 12]. To ensure the quality of service (QoS) of 5G network is sufficient, the LOS effect must be considered in the demand area of 5G communication network [13].

In recent years, with the commercial construction and usage of 5G communication network, the researches on 5G communication network planning have become gradually sufficient. For instance, Palizban et al. [7] used a computational geometry to plan an outdoor millimeter wave network in a dense city, Su et al. [14] used Voronoi tessellation to design the radio access level of 5G mobile networks for the placement of BSs, Ahamed et al. [15] proposed an updated cell architecture with six sectors and an advanced antenna system that provides better 5G coverage. As a valuable tool, geographic information system (GIS) was coupled in 5G communication network planning, Wang et al. [16] based on GIS to explicate the propagation of 5G signals in two-dimensional (2D) spatial framework.

Since the commercial construction and usage of 5G communication network in 2019, it has been planned and constructed for more than 3 years in China. However, the previous researches on the coverage planning of 5G signals are mostly based on 2D spatial framework, for the constructed 5G communication network, there is still a research gap in the evaluation of the coverage of 5G signals in outdoor environment of modern cities from the perspective of 3D spatial framework. Spatial autocorrelation analysis is an important approach to assess the extent of spatial aggregation for variables of interest characterized with global Moran's I index [17], which evaluates whether the pattern expressed is clustered, dispersed, or random. Based on GIS, we analyze the spatial distribution characteristic of 5G base stations with global Moran's I index, and simulate the coverage of 5G signals to the urban road network from the perspective of 3D spatial framework in view of the construction height of 5G BSs in the study area.

2 Study Area and Data

We selected several blocks from Shenzhen city as the study area (see Fig. 1). Shenzhen located in the south of Guangdong Province, China, adjacent to Hong Kong. Guangdong Province, located in the south of Chinese Mainland, is the province with the highest GDP in Chinese Mainland. As of the end of 2021, the GDP of Guangdong had exceeded 2 trillion US dollars, of which Shenzhen had exceeded 464.60 billion US dollars, which is the third city in Chinese Mainland after Shanghai (654.70 billion US dollars) and

Beijing (610.10 billion US dollars). The population of the city is 17 million. The study area of this paper was selected from downtown area of Shenzhen. The total area of the study area is approximately 2.78 km^2. Shenzhen is one of the cities with the largest scale of 5G communication network construction in Chinese Mainland.

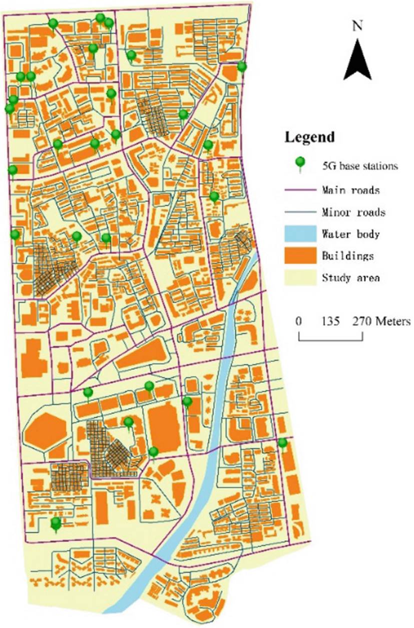

Fig. 1. Map of the study area.

According to the nature of land use, the study area is divided into building area, urban road area and water area. The total area of buildings in the study area is about 0.76 km^2, accounting for about 27% of the study area. The average height of buildings in the study area is about 33.30 m. In this study, we abstract the roads as vector lines. We classify the roads as main roads and minor roads according to the road width. The length of the main roads is about 18.16 km, and of the minor roads is about 68.22 km, the density of the road network in the study area is about 31.07 km/km^2. In addition, there is a section of river in the study area, covering an area of about 0.06 km^2.

We obtained the location and construction height of 5G BSs in the study area from Chinese telecom operators. There are 29 outdoor 5G BSs in the study area, of which 25 BSs were built at the top edge of the building and 4 BSs were erected on the ground, with the height of 4 m to 6 m. The average construction height of the 5G BSs in the study area is about 20.13 m. The data we used in this evaluation research listed in Table 1.

Table 1. Attributes of the data used for 5G signals evaluation in the case study.

Data	Source	Format	Geometry	Spatial reference
Existing 5G BSs	Chinese telecom operators	ESRI Shapefile	Point	GCS_WGS_1984
Buildings	Map world		Polygon	
Roads			Line	

3 Methods

The building density in the study area is approximately 27%, the average height of buildings (33.30 m) is higher than that of 5G BSs (20.13 m). Hence, most 5G signals are blocked by buildings in the study area.

3.1 Spatial Autocorrelation Analysis

Spatial autocorrelation analysis is characterized with global Moran's I index, the z-score and p-value will be returned by the Global Moran's I analysis. Hoping the z-score and the p-value will indicate that we can reject the null hypothesis, because it would indicate that rather than a random pattern at the probability of 10% if the value of the z-score $<$ -1.65 or $>+1.65$.

The global Moran's I statistic for spatial autocorrelation is given as:

$$I = \frac{n}{S_0} \frac{\sum_{i=1}^{n} \sum_{J=1}^{n} w_{i,j} z_i z_j}{\sum_{i=1}^{n} z_i^2} \tag{1}$$

where z_i is the deviation of an attribute for feature i from the mean $(x_i - \overline{X})$, $w_{i,j}$ is the spatial weight between feature i and j, n is equal to the total number of features, S_0 is the aggregate of all the spatial weights:

$$S_0 = \sum\nolimits_{i=1}^{n} \sum\nolimits_{j=1}^{n} w_{i,j} \tag{2}$$

The z_I-score for the statistic is computed as:

$$z_I = \frac{I - E[I]}{\sqrt{V[I]}} \tag{3}$$

where:

$$E[I] = -1/(n-1) \tag{4}$$

$$V[I] = E[I^2] - E[I]^2 \tag{5}$$

$$E[I^2] = \frac{A - B}{C} \tag{6}$$

$$A = n\left[\left(n^2 - 3n + 3\right)S_1 - nS_2 + 3S_0^2\right] \tag{7}$$

$$B = D\left[\left(n^2 - n\right)S_1 - 2nS_2 + 6S_0^2\right] \tag{8}$$

$$C = (n-1)(n-2)(n-3)S_0^2 \tag{9}$$

$$D = \frac{\sum_{i=1}^{n} z_i^4}{\left(\sum_{i=1}^{n} z_i^2\right)^2} \tag{10}$$

$$S_1 = (1/2)\sum\nolimits_{i=1}^{n}\sum\nolimits_{j=1}^{n}\left(w_{i,j} + w_{j,i}\right)^2 \tag{11}$$

$$S_2 = \sum\nolimits_{i=1}^{n}\left(\sum_{j=1}^{n} w_{i,j} + \sum\nolimits_{j=1}^{n} w_{j,i}\right)^2 \tag{12}$$

The relationship between the null hypothesis rejection and the z-score and the p-value is demonstrated in Fig. 2.

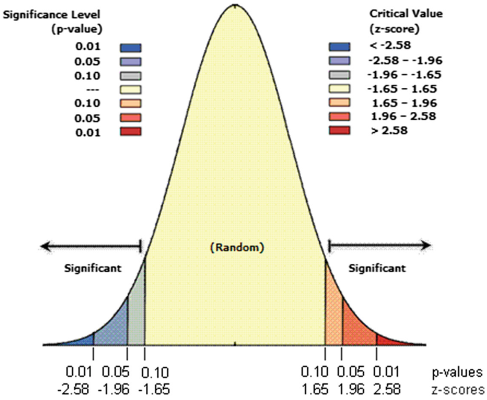

Fig. 2. The relationship between the null hypothesis rejection and the z-score and the p-value.

3.2 Analysis of the Coverage of 5G Signals to Road Network

Wang [16] conducted a coverage model for 5G signals based on the LOS characteristics of 5G signals: discretizing a continuous service space with sampling a series of regular grid points, buildings in study area were modeled as 2D vector polygons in GIS, simulating the 5G LOS service coverage for the maximum effective radius of 200 m of a 5G BS. In this study, the road network in the study area is discretized into points with an interval of 10 m. Combined with the height of the buildings and the construction height of the 5G BSs, the 3D sight lines (see Figs. 3 and 4) of the 5G BSs to the road network represents the LOS service coverage of the 5G BSs to the road network.

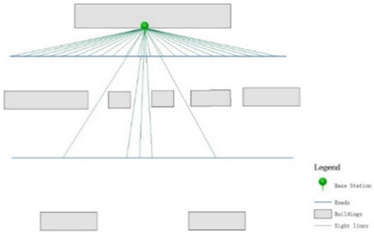

Fig. 3. Propagation of 5G signals in 2D spatial framework.

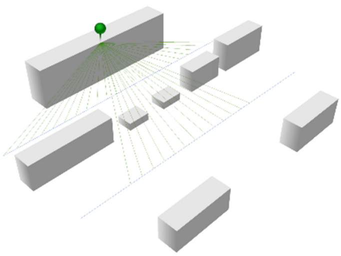

Fig. 4. Propagation of 5G signals in 3D spatial framework.

In this study, we set the reference height of the study area to 0 m, so the heights of the road network and water surface in the study area are set to 0 m. In combination with the height of buildings and 5G BSs in the study area, the 2D vector map of buildings and 5G BSs is converted into 3D vector map based on GIS (see Fig. 5).

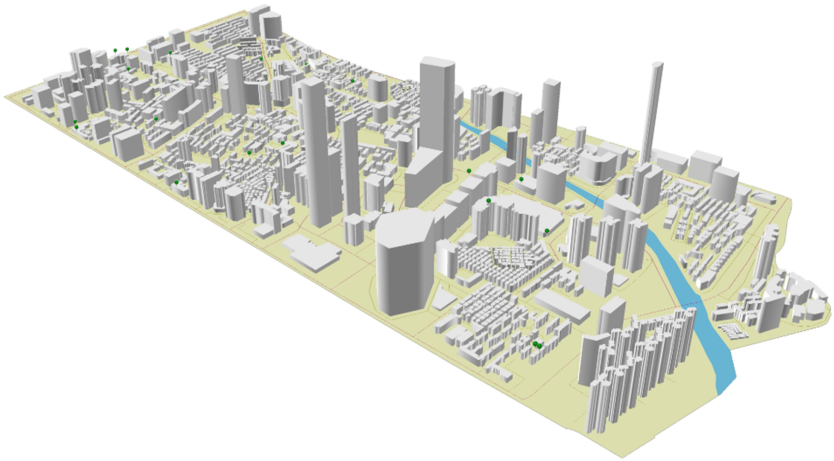

Fig. 5. The study area in 3D spatial framework.

GIS is used to construct the 3D sight lines of the 5G BSs to road network. The coverage radius is set to 200 m [7, 14, 16], count the length of roads covered by 5G signals and calculate the coverage proportion of road network respectively.

4 Results and Discussion

4.1 Spatial Autocorrelation Analysis

The total area of the study area is approximately 2.78 square kilometers. There are 29 5G BSs in the study area, and the density of BSs is about 10.43 BSs/km^2, which is less than the research result of Ge et al. [18] on the construction density of 5G BSs (40–50 BSs/km^2). The value of the Global Moran's I is 0.14, the value of the z-score is 1.06, and of the p-value is 0.28. The value of the Global Moran's I approaches to 0, which can be seen that the spatial distribution of 5G BSs in the study area does not show a significant spatial aggregate or discrete characteristic, but illustrates a kind of random.

Due to the high investment of 5G communication network construction [16], The energy consumption of a single 5G BS is about 4 times that of a 4G BS, meanwhile, the energy consumption of a 5G network is about 12 times that of a 4G network due to the high-density construction of 5G BSs [19]. Hence, 5G communication network construction is not a once-off action, but a step-by-step process [20]. Since the commercial construction and usage of 5G communication network in 2019, the construction of 5G communication network in China has transited from policy-led to technology-driven, and is experiencing a transition from business-led to market-driven [20].

To 5G communication service providers, the profits earned from enterprise users are higher than individual users. At current period, the construction of 5G communication network in China gives priority to serving enterprises to develop applications such as IoT and AI. 5G unmanned vehicles application in open roads is limited by native laws. The construction of 5G network which to cover urban outdoor area mainly serves individual 5G users, 5G communication service providers tend to choose relatively high population density area in urban outdoor environment as priority to the coverage of 5G signals.

4.2 Analysis of the Coverage of 5G Signals to Road Network

Combined with the height of the buildings and the construction height of the 5G BSs, the 3D sight lines (see Fig. 6 and Fig. 7) of the 5G BSs to the road network represents the LOS service coverage of the 5G BSs to the road network. The total length of the roads in the study area is about 86.38 km, and the length of the roads covered by 5G signal is 16.32 km after simulation, with a coverage ratio of about 18.89%. Among them, the coverage length of the main roads is 6.78 km, and the coverage proportion is 37.32%, which of the minor roads is 9.54 km, with a coverage ratio of 13.98%.

In researches of the coverage of 5G signals in urban outdoor area, Wang [16] discretized a continuous service space with sampling a series of regular grid points as the demand and coverage area of 5G signals. The road area is one of the areas with the largest demand for 5G communication network services in urban outdoor area. We take the urban road network as the research object of 5G signals coverage, which represents

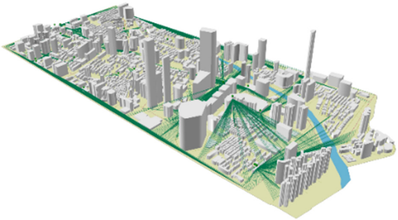

Fig. 6. The 3D sight lines of the BSs to the road network in the study area.

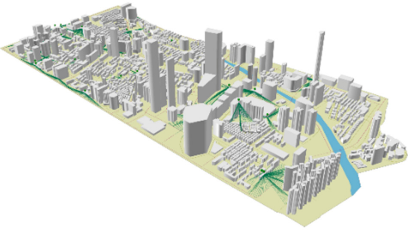

Fig. 7. The 3D sight lines of the BSs to the road network in the study area with 200 m coverage radius.

the coverage of 5G signals to urban outdoor environment to some extent. Palizban et al. [7] and Wang et al. [16] explicated the propagation of 5G signals in 2D spatial framework, Su et al. [14] designed the placement of base stations at low and high network load in the same perspective. Wang [16] simulated the propagation of 5G signals using Buffer and LOS analysis.

With high building density in modern cities, the construction height of 5G BSs must be considered. The LOS coverage research on 5G signals based on the construction height of 5G BSs from the perspective of 3D spatial framework would provide decision support for 5G communication networks construction and optimization in modern cities.

5 Conclusions

5G will play an essential role in the development of science and technology. A high-frequency millimeter wave was adopted in 5G communication technology as a basic wireless network technology, which with the characteristic of huge amount of data carriage but over a short distance, so the effective coverage radius of most 5G BSs is shorter than the previous communication networks, such as 3G and 4G. Since the commercial construction and usage of 5G communication network in 2019, it has been planned and constructed for more than 3 years in China. Approaches to evaluate the coverage of 5G signals in outdoor environmental in modern cities in China deserves to be explored. The road area is one of the areas with the largest demand for 5G communication network services in urban outdoor area. We take the urban road network as the research object of 5G signals coverage, which represents the coverage of 5G signals to urban outdoor environment to some extent.

Spatial autocorrelation analysis is an important approach to assess the extent of spatial aggregation for variables of interest [17]. In this study, we conducted spatial autocorrelation analysis on the spatial distribution of 5G base stations in the study area, and found that the characteristic of the spatial distribution of 5G BSs illustrates a kind of random rather than aggregate or discrete.

Due to the construction investment and energy consumption of 5G communication network are higher than the previous communication networks, such as 3G and 4G [16, 19], the construction of 5G communication network needs to be built on demand. The construction of 5G network which to cover urban outdoor area mainly serves individual 5G users, 5G communication service providers tend to choose relatively high population density area in urban outdoor environment as priority to the coverage of 5G signals.

In the previous 5G network planning studies, most of them are in the 2D spatial framework. In the 5G BSs construction issues, the height is the natural attribute of the base stations. For the evaluation of the coverage of 5G signals, the construction height of 5G BSs needs to be considered. The LOS coverage research on 5G signals based on the construction height of 5G BSs from the perspective of 3D spatial framework would provide decision support for 5G communication networks construction and optimization in modern cities.

In the paper, we established a 3D model of the buildings and 5G BSs distribution in the study area, combined with the height of the buildings and the construction height of the 5G BSs, the 3D sight lines of the 5G BSs to the road network represents the LOS service coverage of the 5G BSs to the road network. The result shows that the length of the main roads which covered by 5G signals in the study area is about 3 times that of the minor roads. As urban main roads were built to carry more traffic and people than minor roads, the research result also verifies the on-demand construction mode of the construction of 5G communication networks in Chinese modern cities to a certain extent.

Nevertheless, limitations still exit in this study. Further researches should focus on the space-time distribution of population density in the study area. According to the population density, the construction and optimization of 5G communication network in the study area needs to be carried out at the next step, and the energy consumption of 5G BSs in the study area could be precisely controlled according to the temporal and spatial distribution of the population.

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