URBAN INTERFACE DESIGN STRATEGIES BASED ON THE ADAPTABILITY OF 5G MILLIMETRE WAVE MOBILE COMMUNICATION

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ABSTRACT

The Internet of Things presupposes ubiquitous coverage of 5G mobile communication base stations (BSs), while the current urban space becomes an obstacle to the efficient coverage of 5G mobile communication signals. The reason for the obstruction begins with the qualitative change of the physical properties of 5G signals. Due to its high frequency, poor penetration and small coverage, millimetre wave signals (MMW) will be blocked when encountering physical obstacles in urban space and can't continue to be transmitted. Therefore, MMW depends on line-of-sight transmission, there is no occlusion between the BSs and people. So the signal in the 5G era creates a requirement for urban physical space. Under the condition that the urban space is unchanged, the major of mobile communication can't fundamentally solve the shielding problem of MMW in the space, and can only obtain the continuity of signal coverage by increasing the BSs. In addition, the energy consumption and quantity of 5G BSs are several times that of 4G BSs, so the deployment cost of 5G is high and the channel coverage effect is limited. Based on the above problems and the current research status, the purpose of this study is to clarify the relationship between urban space and mobile communication channels represented by MMW, and explore how to integrate the demand of millimetre wave channel coverage for urban space into the existing methodology of landscape architecture design. In order to find a balance between the needs of traditional factors and the urban space needs of MMW channel coverage, it not only meets the traditional needs, but also improves the urban space conditions of MMW channel coverage to a certain extent. That is to explore the methodology of architecture and landscape architecture design that takes MMW channel as a new reference factor.

KEYWORDS _ *Urban Interface, 5G millimetre wave, Adaptability, New factor, Methodology*

INTRODUCTION

The contradiction

As early as the 1960s, when mobile communication was not widely used by the general public, Lewis Mumford keenly observed the networked nature of cities, referring to the invisible world filled with cables, wires, connections, encoding, protocols, and capital as the "invisible city"(Lewis Mumford, 1961). "Smart Cities" in 2009. IBM states that Smart Cities employadvanced information and communication technologies (ICT) to integrate the various core systems of urban operations, including people, businesses, transportation, communication, water, and energy, transforming them into a "system of systems" that operates in a more intelligent manner, thereby promoting sustainable urban development(IBM Institute for Business Value, 2009).

The ultimate goal of human communication is to enable anyone to exchange any type of information with anyone, anytime, and anywhere, known as "Internet of Things." Mobile communication serves as the essential pathway to achievethis goal.

As a new infrastructure, 5G serves as the foundation for the Internet of Things and smart cities. The vision of the Internet of Things relies on the ubiquitouscoverage of 5G mobile communication base stations. However, the current urbanspace poses obstacles to the efficient coverage of 5G mobile communicationsignals.

The use of high-frequency millimeter waves (mmWave) in 5G communication technology enables the transmission of large amounts of data over short distances (Bai & Heath, 2015). However, the atmospheric absorption and high penetration loss of mmWave pose challenges to the coverage radius of 5G base stations (BSs), which is significantly smaller compared to previous technology layers such as 2G, 3G, and 4G (Maccartney, Zhang, Nie, & Rappaport, 2013; Sulyman et al., 2014).

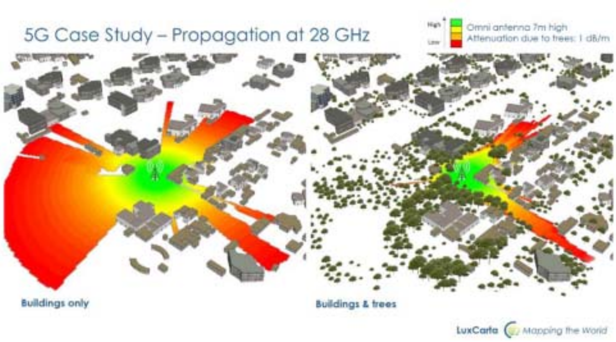


Figure 1: Barcelona Telecom Tower; **Figure 2:** Propagation diagram of 28 GHz millimeter waves in urban environment

Furthermore, the dense distribution of buildings in urban areas restricts the propagation and coverage of 5G signals. According to Pi and Khan (Pi and Khan, 2011), even common building materials like brick and concrete exhibit high penetration loss for mmWaves in urban areas, resulting in significant indoor-outdoor isolation (Palizban, Szyszkowicz, & Yanikomeroglu, 2017). This phenomenon of penetration loss in 5G propagation is known as the Line-of-Sight (LOS) effect (Al-Falahy & Alani, 2019; Maccartney et al., 2013; Qamar et al., 2019). Therefore, mmWave experiences high penetration and path loss (Lee et al., 2018; Maccartney et al., 2013), susceptibility to interference (Bai & Heath, 2015), and sensitivity to environmental blockage (Sulyman et al., 2014). It is essential to consider LOS coverage in the target areas to ensure satisfactory Quality of Service (QoS) for 5G (Rappaport et al., 2013).

Clearly, the propagation characteristics of mmWave present significant investment cost challenges for the deployment of 5G. Telecom operators must deploy ultra-dense base stations in urban areas to achieve satisfactory service coverage. In recent years, energy-efficient technologies (Buzzi et al., 2016) and the upgrade of 4G BSs to 5G BSs (Sharma et al., 2018) have gained considerable attention in reducing the construction and operation costs of 5G cellular networks.The initial 5G rollout often involves Non-Standalone (NSA) deployment using existing 4G base stations. However, to minimize construction costs, it is crucial to cover the target area with the minimum number of base stations. The total investment for deploying a new 5G base station in China is approximately $53,000. Upgrading 4G base stations to 5G can reduce costs, but additional base station locations are still required to meet the coverage demands of 5G services.

CURRENT COUNTERMEASURES

Research on the obstruction of millimeter-wave mobile communication in urban spaces can be divided into two categories: studies within the field of mobile communication and studies outside the field of mobile communication.

A. Mobile Communications

Within the field of mobile communication, researchers investigate the physical properties of millimeter waves and develop methodologies to adapt the millimeter wave channel to urban physical spaces.

The research on the obstruction of millimeter-wave mobile communication in urban spaces within the field of mobile communication aims to develop methodologies for millimeter wave base station deployment by studying the physical properties of millimeter waves and the morphology and materials of urban spaces. Mobile communication professionals are not the direct shapers of urban spaces, nor are they researchers in the field of materials. Urban spaces exist in mobile communication research as unalterable limiting conditions. Therefore, the propagation characteristics of millimeter waves present significant investment cost challenges for the introduction of 5G. To achieve satisfactory service coverage, 5G telecom operators must deploy ultra-dense base stations in urban areas. This limitation is inherent in the fifth generation of mobile communication development, as it cannot fundamentally solve the problem of signal coverage through technological advancements alone. Hence, the limitations imposed by space and materials require supplementation from disciplines outside the field of mobile communication. It is imperative to conduct research in architecture and landscape architecture to explore scene design from the perspective of 5G.

Other majors

Research on spatial optimization models for cellular network planning has a long history, focusing on maximizing service coverage. However, existing heuristic models face challenges in simulating line-of-sight (LOS) propagation and coverage of 5G signals in urban areas. Most models are designed for 2G/3G/4G networks and lack consideration of the higher penetration loss of 5G signals. Recent studies have utilized GIS to optimize 5G network planning but lack global optimization capabilities. Spatially-implicit heuristic algorithms have been developed to minimize penetration loss, but they overlook the three-dimensional morphology of urban buildings. Current modeling algorithms simplify buildings into two-dimensional planes, leading to inaccurate results(Wang Q, Zhao X, Lv Z, et al. 2020). The lack of active modification of the millimeter wave coverage environment hinders achieving both low cost and high efficiency. Overcoming these challenges is crucial for informed decision-making and improving millimeter wave coverage efficiency.

THEORETICAL CONSTRUCTION

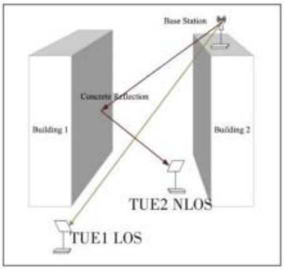
Theoretical foundation

A. Infrastructure Architecture

The concepts of “Architecture as Infrastructure” and “Infra-architecture” have similarities but differ in emphasis. “Architecture as Infrastructure” involves designing architecture as part of urban infrastructure for sustainable and smart cities, focusing on the connection between architecture and urban infrastructure. In contrast, “Infra-architecture” integrates infrastructure and architecture, creating a new form that provides various functions and aims for a more adaptable urban environment. This study examines the interface of urban public spaces, particularly in relation to mmWave mobile communication. Mobile communication, as a gray infrastructure, possesses inherent infrastructure attributes. Infrastructure architecture research and theories serve as the foundation for this study. Scholars have developed frameworks for infrastructure, including concepts like “Thick 2D” and “Infrastructural Urbanism” by Stan Allen, “Terrain Vague” by de Sola Morales, and “Organization Space” by Keller Easterling(Kazys Varnelis, 2008; Tan, Z. 2016). These theories address the failure of modernism and the autonomy of infrastructure, aiming to reconstruct urban architectural discourse. This research focuses on the adaptability of urban interfaces to mmWave mobile communications within this context, aiming to revitalize the architectural discipline’s engagement with cutting-edge urban issues.

B. Complex Adaptive System (CAS)

Complex Adaptive System (CAS) theory combines Adaptation and Complexity theory, representing a significant branch of complexity science(Holland J H. 2000). Adaptation refers to the adjustment of organisms’ genetic composition and characteristics to align with their environment’s development. It spans various fields, ranging from individuals to entire ecosystems. Organisms are considered adaptive agents, while the environment serves as the object of adaptation. Ecological adaptation initially applied to natural ecosystems has been analogously extended to human systems, including economics, society, and culture. Economic adaptation studies analyse the relationship between adaptive agents and economic development, while social adaptation research examines changes in psychological and behavioral patterns in response to the social environment. Cultural adaptation research explores how regions adjust their behavior according to the natural environment.



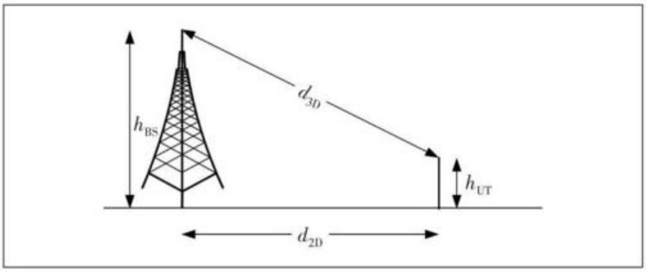


Figure 3: Outdoor Line-of-Sight (LOS) propagation diagram in an urban environment
Figure 4: Comparison of LOS & NLOS channels

In “The New Science of Cities,” Michael Batty argues that cities should be viewed as complex systems composed of networks and flows(Batty M. 2013). Within the urban CAS, mmWave mobile communication acts as a crucial infrastructure for enhancing network strength and supporting necessary flows to meet human needs.

Visual Analysis of millimeter wave coverage

A. Information collection

The coverage of millimeter-wave mobile communications depends on Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) scenarios (Fig.4). Controlled variable experiments, similar to the feather and lead ball falling freely in a vacuum, are used to demonstrate scientific principles. This study focuses on the physical properties of millimeter-wave, such as signal attenuation, base station height, coverage distance, range, and signal reflection from different surfaces.

The attenuation of millimeter-wave mobile communication signals can be described using a path loss model, where the attenuation value is a function of distance and other relevant factors. One commonly used path loss model is the free space propagation model, with the following formula:

Attenuation (dB) = 20 * log10(d) + 20 * log10(f) + C

Where:

Attenuation: The loss of signal during propagation, measured in dB.

d: Transmission distance, i.e., the distance over which the signal propagates, measured in meters.

f: Signal frequency, measured in Hertz.

C: Constant that incorporates other factors related to the propagation environment and system, such as antenna gain, environmental attenuation, etc.

According to the attenuation formula of the free space propagation model, it can be observed that as the distance increases, the attenuation value also increases. This is because the signal encounters free space path loss during propagation, and with increasing distance, the signal energy weakens inversely proportional to the square of the distance, as Fig.3 shows.

According to the research conducted by Gao et al., for millimeter-wave base stations, 0≤D3d≤150m. Based on Fig.3, 0≤D2d≤D3d, which implies 0≤D2d≤150m. In this study, D2d is set to 130m, and hbs is 25m.

About the layout of the base station, prior to 5G, the signals operated in the low-frequency range, including centimeter-wave signals. As a result, the impact of buildings and other structures in urban areas on signal coverage could be considered negligible. Consequently, base station deployments exhibited a cellular pattern, as depicted in the left image of Figure 5. However, with the advent of 5G, the presence of obstacles such as buildings significantly affects signal propagation, leading to irregular coverage patterns for base stations, as illustrated in the right image of Figure 7.

In contrast to current network deployments, which divide a macro-cell uniformly into smaller areas covered by a few light base stations, dense heterogeneous networks significantly increase the density of infrastructure nodes per unit area. These networks opportunistically deploy and activate a large number of heterogeneous infrastructure nodes, including macro base stations, femtocells, and relays, in response to demand. As a result, the network layout becomes irregularly shaped, as illustrated in Figure 5.

B.Parametric analysis model

After collecting the aforementioned data, we constructed an analysis model that can simulate signal coverage in urban space. The analytical logic of this analysis model is shown in Fig.5 & Fig.6.

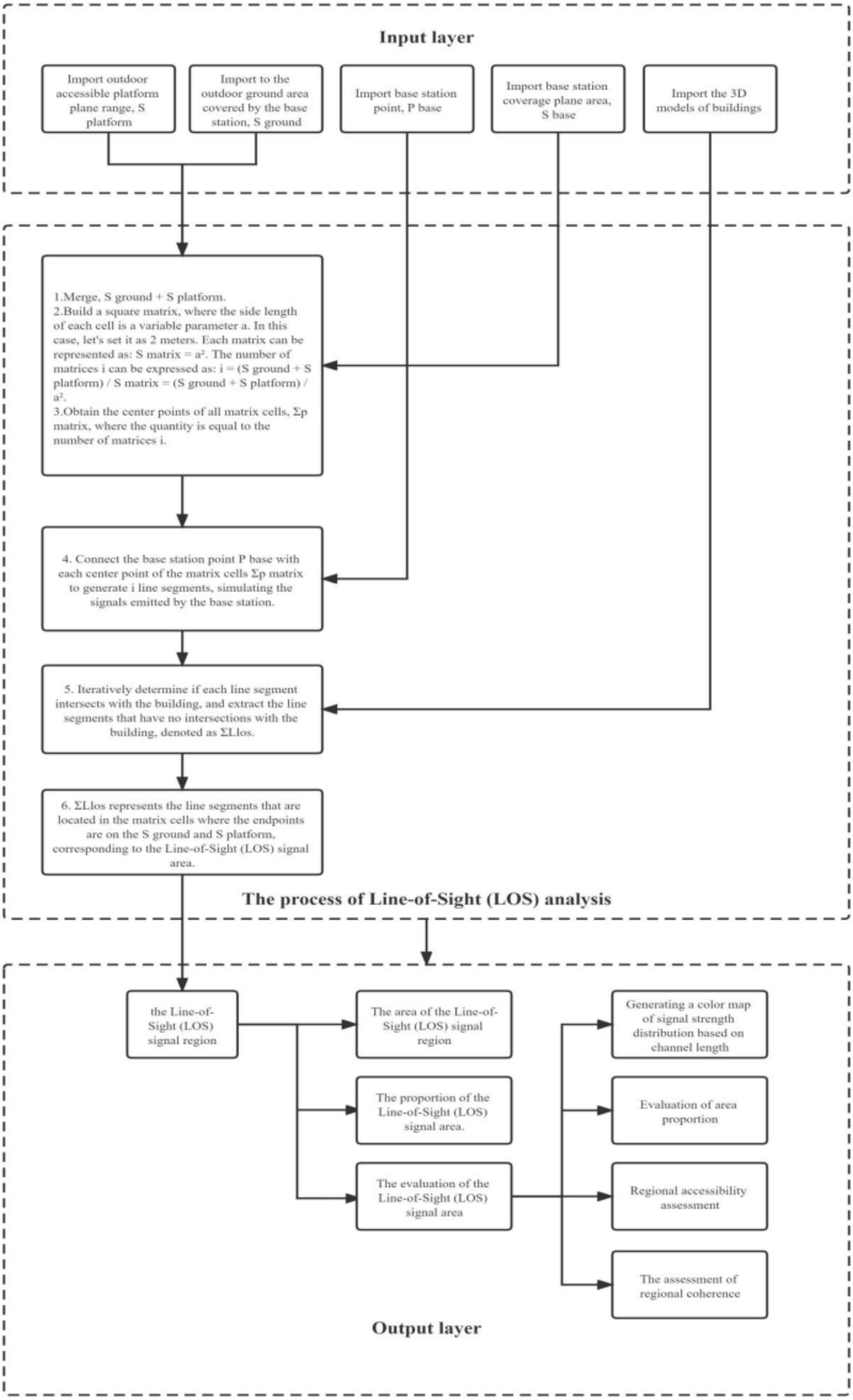
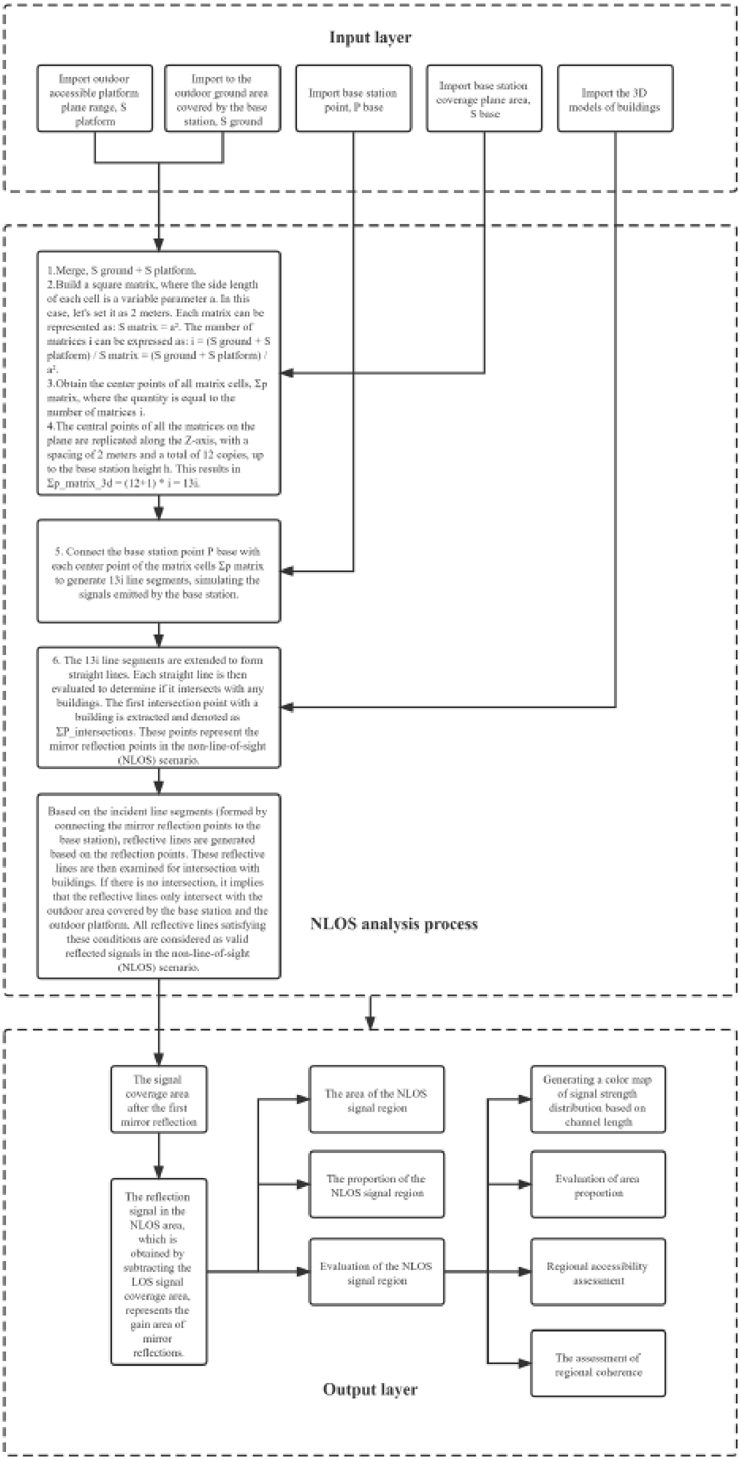


Figure 5: The technical methodology for conducting Line-of-Sight (LOS) analysis of the scene



1.Merge, S ground + S platform.
2.Build a square matrix, where the side length of each cell is a variable parameter a. In this case, let's set it as 2 meters. Each matrix can be represented as: S matrix = a^2. The number of matrices i can be expressed as: i = (S ground + S platform) / S matrix = (S ground + S platform) / a^2.
3.Obtain the center points of all matrix cells, Σp matrix, where the quantity is equal to the number of matrices i.
4.The central points of all the matrices on the plane are replicated along the Z-axis, with a spacing of 2 meters and a total of 12 copies, up to the base station height h. This results in Σp_matrix_3d = (12+1) * i = 13i.

5. Connect the base station point P base with each center point of the matrix cells Σp matrix to generate 13i line segments, simulating the signals emitted by the base station.

6. The 13i line segments are extended to form straight lines. Each straight line is then evaluated to determine if it intersects with any buildings. The first intersection point with a building is extracted and denoted as ΣP_intersections. These points represent the mirror reflection points in the non-line-of-sight (NLOS) scenario.

Based on the incident line segments (formed by connecting the mirror reflection points to the base station), reflective lines are generated based on the reflection points. These reflective lines are then examined for intersection with buildings. If there is no intersection, it implies that the reflective lines only intersect with the outdoor area covered by the base station and the outdoor platform. All reflective lines satisfying these conditions are considered as valid reflected signals in the non-line-of-sight (NLOS) scenario.

The reflection signal in the NLOS area, which is obtained by subtracting the LOS signal coverage area, repesents the gain area of mirror reflections.

Figure 6: The technical methodology for conducting Line-of-Sight (NLOS) analysis of the scene

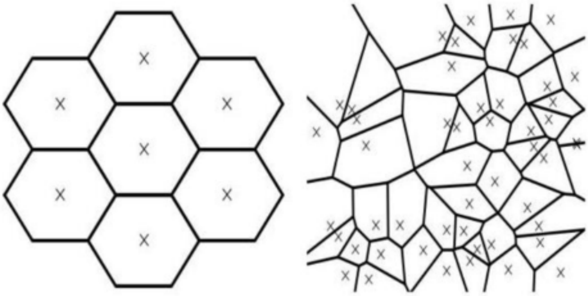


Figure 7: Evolution of cellular network layout. On the left is the traditional layout, and on the right is the 5g layout

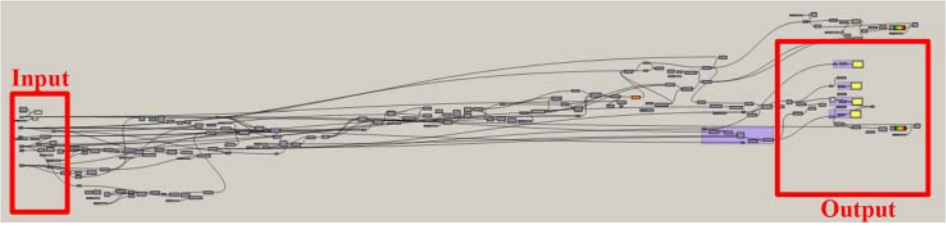
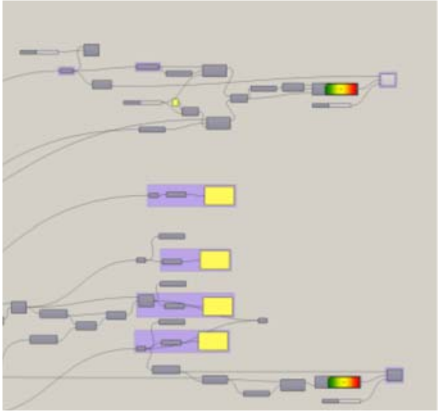


Figure 8: Analysis model in Grasshopper (Image source: Self-drawn by the author)



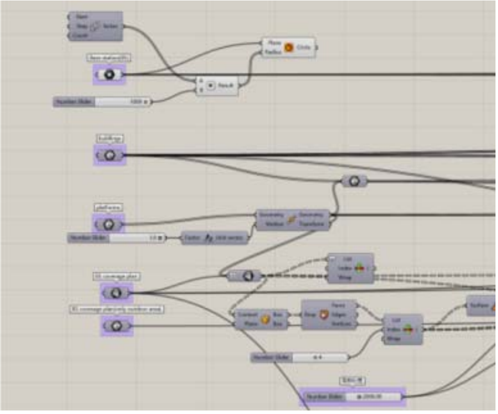


Figure 9: Input of analysis model in Grasshopper (Left)
Figure 10: Output of analysis model in Grasshopper (Right)

CASE ANALYSIS

The analysis model imports a simplified version of Galaxy Soho into Grasshopper for Rhinoceros. It includes three-dimensional models of buildings and urban landscape infrastructure. The analysis evaluates line-of-sight (LOS) and first-order mirror reflection transmission of millimeter-wave signals. LOS transmission assesses obstructions between arbitrary locations and the base station, while mirror reflection transmission calculates signals reflected by building facades, reaching outdoor terraces and rooftops without secondary obstructions. The analysis simplifies by disregarding horizontal dimensions of architectural elements, focusing on signal obstacles presented by buildings.

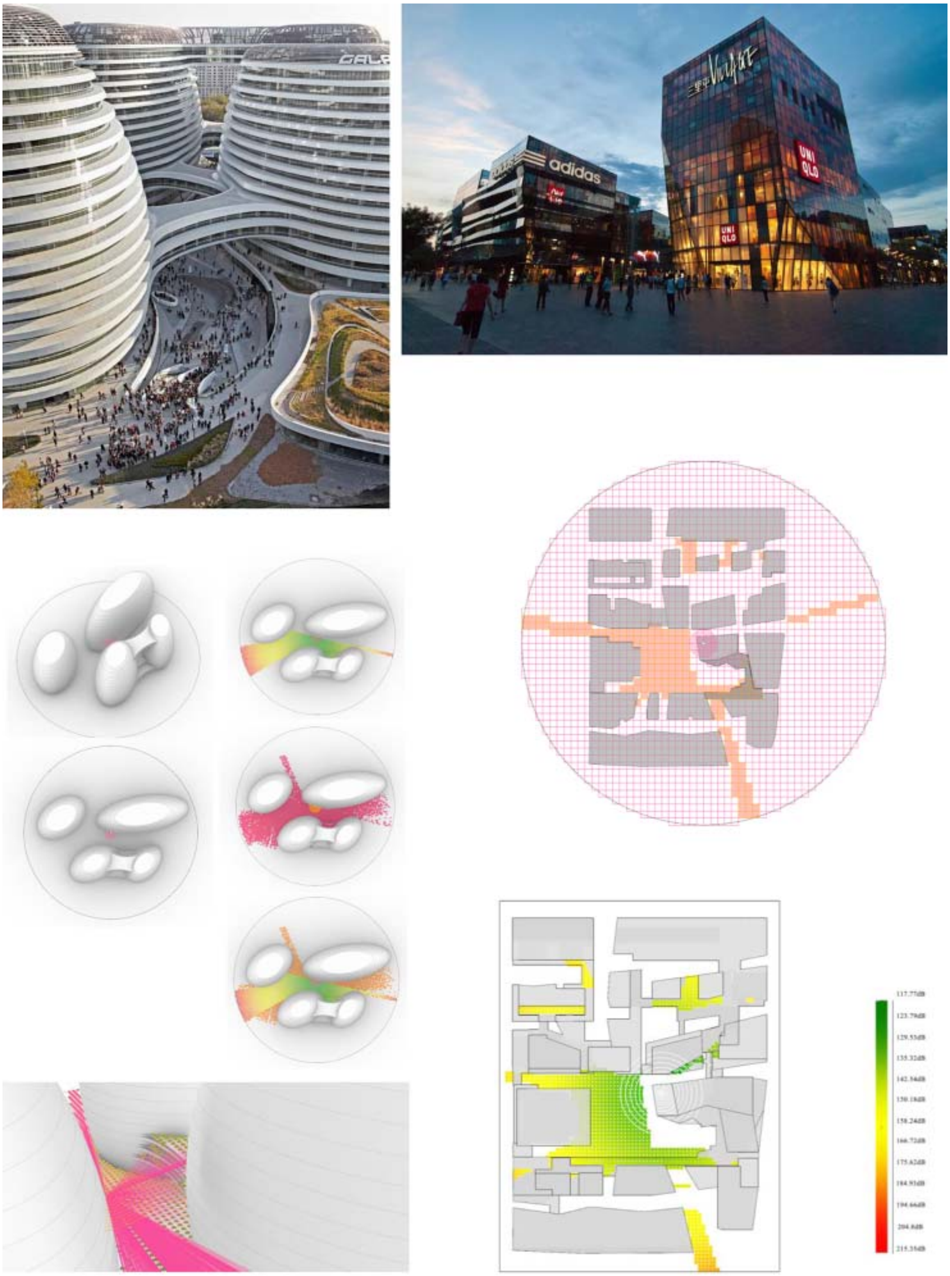


Figure 11: Parameter Analysis of Galaxy SOHO and TaiKoo Li Sanlitun

Deployment locations of the base stations, which are imported into the analysis model as spatial coordinate points. It should be noted that the determination of base station deployment locations also needs to satisfy certain criteria, requiring the construction of an independent parameterized analysis model. The analysis model includes the following:Horizontal coverage range of the base station.Vertical signal coverage range determined by the height of the base station.Outdoor rooftops accessible to pedestrians.By outputting the number of matrices occupied by LOS and NLOS signal coverage through the parametric model in Grasshopper, data such as signal coverage area and ratio can be obtained.

In the case of Galaxy SOHO, the LOS area occupies 1656 matrices, while the total number of matrices in the outdoor reachable area is 11857. Therefore, the area of the LOS region is 1656*4=6624 square meters, with a ratio of 1656/11857≈0.140. The effective signal coverage area obtained through mirror reflection in the scene is 2402 matrices. Subtracting the overlapping portion with the LOS coverage area, the signal coverage area of the NLOS scenario is 880 matrices, corresponding to an area of 3520 square meters, with a ratio of approximately 0.074. After combining both, the total signal coverage area is 2536 matrices, corresponding to an area of 5176 square meters, with a ratio of approximately 0.214.Thus, the signal coverage rate of Galaxy SOHO is 21.4%.

By analyzing different urban spaces with varying plot ratios and morphologies, the correlation and correlation degree between millimeter-wave signal coverage and factors such as plot ratio, building spacing, and building height can be obtained. Due to limited space, this section is not presented in this paper. Same analytical approach was also applied to study the millimeter-wave adaptability in the Sanlitun Taikooli neighborhood, as briefly presented in Figure 11.

SIGNAL ENVELOPE

Regarding the incremental design methods for urban public space interfaces from the perspective of millimeter-wave adaptability, reference can be made to the concept of the “solar envelope” in the context of solar-responsive urban design.

In 1974, Nourse published his first book titled “Energy and Form: The Ecological Approach to Urban Growth,” in which he introduced the design method of the “solar envelope” for controlling the interface form of buildings based on solar adaptability to regulate the overall form of the city(Knowles R L. 1974), as Fig.12 shown. Forty-two years later, in September 2016, the Harvard Graduate School of Design (GSD) organized a two-day conference called “Heliomorphism,” the inaugural event of the Urbanization Lab created by architect and urbanist Charles Waldheim. The conference served as a platform to explore Nourse’s research on the “solar envelope,” which is a legal provision that, if implemented as policy, would ensure the utilization of solar energy in urban areas. The concept of the “solar envelope” continues to have a wide-ranging impact to this day, as illustrated in Fig. 13.

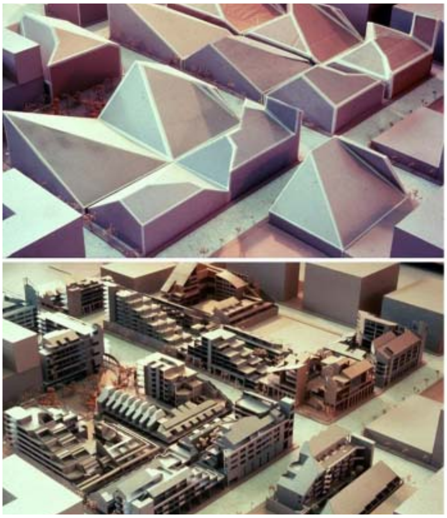
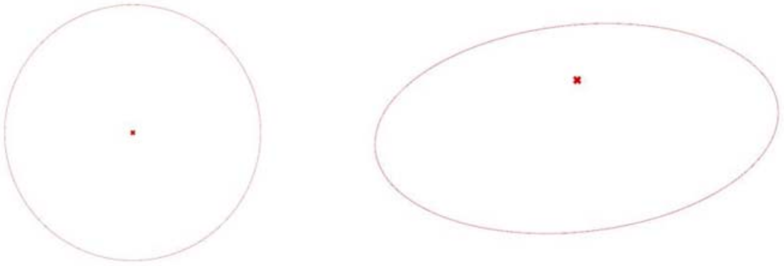
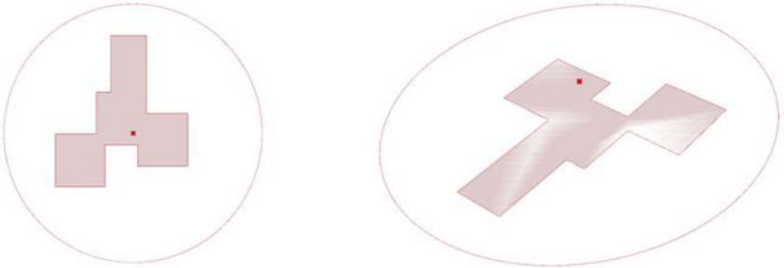


Figure 12: Left, “Solar envelope”; **Figure 13:** Right, VIΛ 57 West, designed by BIG, New York

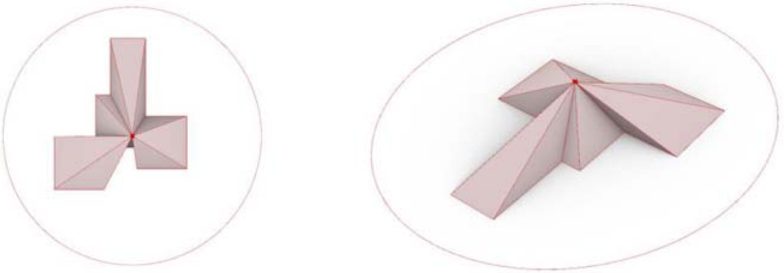
Building upon the theoretical foundation of complex adaptive systems discussed earlier, the research defines the adaptation design of urban public space interfaces for millimeter-wave (mmWave) communications as the "signal envelope." The underlying logic of the "signal envelope" stems from the essence of the study, which involves striking a balance between the requirements of the mmWave mobile communication channel and the spatial demands of mmWave applications in urban environments. This necessitates the allocation of mmWave coverage based on specific spatial needs, whereby the initial design incorporates the spatial requirements of mmWave application scenarios along with other elements of spatial design (such as traffic flow, green spaces, recreational areas, and other infrastructure needs). The mmWave coverage range is then delineated around the base station locations, forming a three-dimensional space known as the Line-of-Sight (LOS) mmWave channel.



Base station site and coverage area



The spatial range of millimeter wave application requirements



Space required for LOS millimeter wave channel

Figure14: "Signal envelope"in Grasshopper

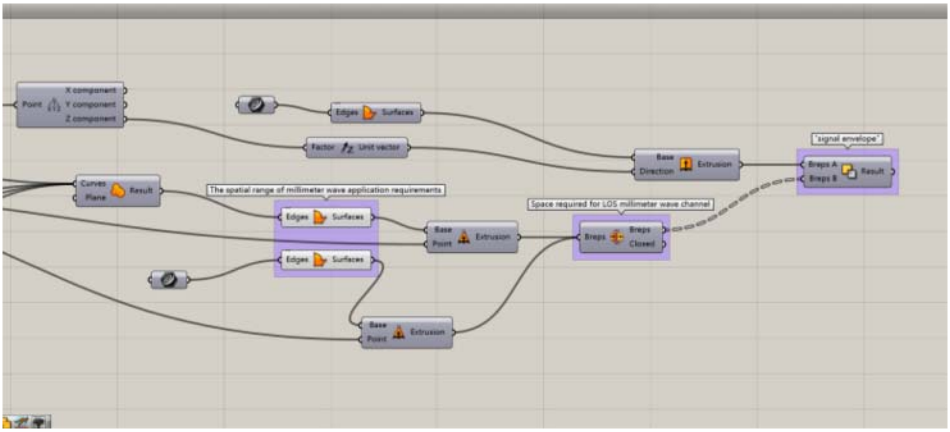


Figure 15: visualization of "Signal envelope

The negative space within this three-dimensional envelope represents the "signal envelope." In the design of buildings and landscape structures, as long as they do not exceed the boundaries of the "signal envelope," the alignment between the spatial requirements of mmWave application scenarios and the needs of the mmWave channel can be ensured, as shown in Fig.14, Fig,15.

CONCLUSIONS

The advancement of 5G technology using millimeter waves (mmWaves) is crucial for various applications, offering high-speed and low-latency wireless communication. However, mmWaves have limited coverage due to propagation and penetration characteristics, posing challenges for building penetration in urban areas. This requires denser base station deployment, leading to significant investments and increased energy consumption. Existing spatial optimization models oversimplify urban buildings into 2D planes, resulting in inaccurate calculations for three-dimensional coverage in line-of-sight (LOS) scenarios. Lack of analysis of height variations and complex structures further hampers accuracy. This study proposes an innovative approach based on infrastructure architecture and complex adaptive systems to enhance mmWave coverage efficiency. It introduces a simulation system and analysis tools to quantify the relationship between spatial morphology and LOS scenarios, enabling further research on adaptive design. The concept of the "signal envelope" guides the design of mmWave-enabled urban spaces, aiming to inspire academia and strengthen the role of architecture in urban issues.

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