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Ground-to-air wireless coverage extension for 6G: a triangular prism structure-based approach

Junyu LIU[1], Min SHENG[1*], Jiandong LI[1,2], Xuhui CHEN[1] & Chenxi ZHAO[1]

[1]*State Key Laboratory of Integrated Service Networks, Xidian University, Xi'an* 710071*, China;*
[2]*Department of Broadband Communication, Peng Cheng Laboratory, Shenzhen* 518000*, China*

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Stimulated by the requirements of passenger transport, cargo delivery, security monitoring, etc., the development of a low-altitude economy has been entering a new stage [1]. Relying on the low-altitude airspace below 1000 m, the low-altitude economy is a comprehensive economic form, which is towed by various low-altitude flight activities of civil-manned and unmanned aerial vehicles. One key factor for the development of the low-altitude economy is to provide seamless three-dimensional (3D) coverage for low-altitude airspace in a cost-efficient way. However, the existing terrestrial mobile communications systems, including the fourth-generation (4G) and fifth-generation (5G) systems, are mainly designed to provide terrestrial coverage. Coverage extension is infeasible due to the inherent coverage structure and the downward-tilted antennas. Other approaches including using satellite [2] or drone base stations also fall short of coverage extension. Specifically, the limitations on the available bandwidth and long-distance transmission in satellite coverage may be the bottlenecks to serving aerial users with the requirements of high transmission rate and low end-to-end latency. Besides, the limited flight time makes it difficult for drone base stations to provide long-time stable coverage. Since the main object of the low-altitude economy is the urban area with dense population distribution, it is an efficient way to enable ground-to-air (G2A) coverage extension of the terrestrial mobile communication system for 3D low-altitude airspace coverage in the future sixth-generation (6G) system.

The coverage structure of the existing mobile communication system is designed to achieve seamless terrestrial coverage. Enabling coverage extension to the low-altitude airspace using the existing coverage structure would result in the problems of under-coverage and over-coverage. Specifically, under-coverage refers to the existence of spatial coverage holes, which are caused by simply extending the terrestrial structures and antenna beams of small vertical beamwidth. Over-coverage refers to the coverage overlaps of beams, which results in severe inter-cell interference within the system. In light of these problems, this study proposes a triangular prism-based 3D coverage structure and G2A coverage expansion method. On the premise of ensuring seamless 3D coverage, the spatial overlap of different beams could be minimized so as to effectively avoid the inter-cell interference. Field test results show that the G2A coverage extension approach can achieve a coverage rate of more than 99% in the spatial area below 300 m.

Before we introduce the 3D coverage structure in detail, we first review the two-dimensional (2D) coverage structures in terrestrial mobile communication systems. To provide seamless coverage for terrestrial users, there are three basic 2D coverage structures including triangular, quadrilateral, and hexagonal structures, which are shown at the top of Figure 1(a). Among them, the hexagonal structure has been widely used, aided by which the terrestrial base stations (TBSs) are deployed at the center of the hexagon and form a cellular-shaped coverage structure [3]. Since each TBS can achieve omnidirectional radiation through utilizing multiple directional-antenna sectors, the overlap of the coverage area of adjacent TBSs is the minimum under the hexagonal structure, compared with the triangular and quadrilateral structures.

For the G2A coverage extension, the design of 3D coverage structures is based on triangular, quadrilateral, and hexagonal structures as well to achieve 3D seamless coverage. Considering the coverage in the vertical dimension, triangular, quadrilateral, and hexagonal prisms could serve as the basic 3D coverage structures. Since the low-altitude airspace could be filled by adjacent prisms, the essence of the design is to reduce the inter-prism overlap. To this end, we analyze the overlapping rates of the three 3D coverage structures, which are given at the bottom of Figure 1(a). Different from the terrestrial coverage, it indicates that the triangular prism coverage structure has the smallest inter-prism overlapping rate. The reason is that involving too many TBSs in coordinated coverage in quadrilateral and hexagonal prisms would create redundant coverage structures that have more beam and signal overlaps. Therefore, the triangular prism serves as the optimal G2A coverage structure.

After the discussion of triangular prism-based 3D coverage structure, we then introduce the steps of the G2A coverage expansion method.

Step 1. Generating triangle meshes with Delaunay triangulation. Delaunay triangulation can maximize the size of the minimum angle in each triangle to avoid elongated triangles, and the triangle meshes generated by De-

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[*] Corresponding author (email: msheng@mail.xidian.edu.cn)

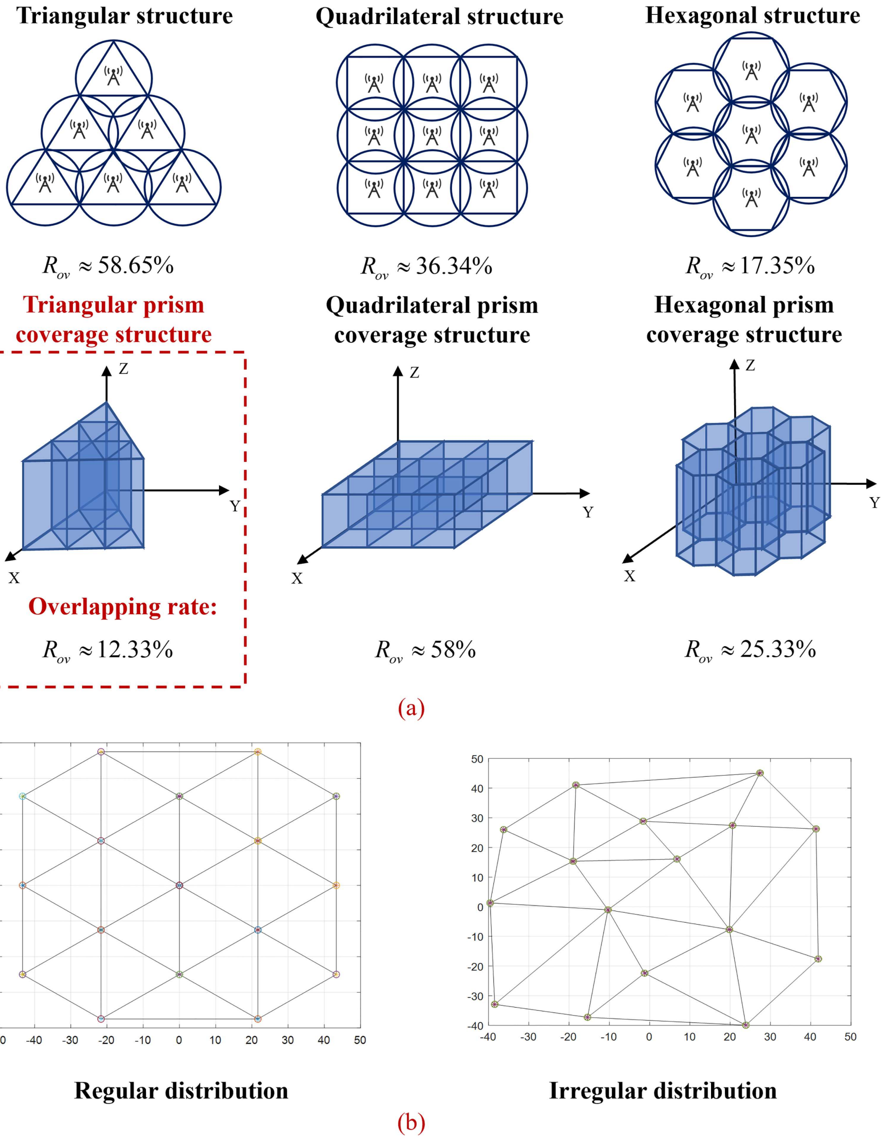

Figure 1 (Color online) (a) 2D coverage structures of triangles, squares, and hexagons and their 3D coverage structures. (b) Triangulation of networks with regular and irregular distributions of TBSs. In (a), r denotes the sector coverage radius, and H denotes the height of the area to be covered. r and H are set to be 100 and 300 m, respectively. In (b), each dot denotes the locations of a TBS.

launay triangulation are of uniqueness [4]. In consequence, all the triangle meshes generated based on any set of base station (BS) locations in the plane would be more regular. Therefore, the variance of the horizontal beamwidth and transmit power of each BS sector would be minimized. Moreover, the triangle meshes are of good scalability, which is helpful to the network deployment in practice. Triangulation of networks with regular and irregular distributions of TBSs is illustrated in Figure 1(b). For the case of TBS irregular distribution, since TBSs may have different numbers of sectors, a combination of adjacent sectors is performed. Specifically, adjacent sectors with identical vertical beamwidths and antenna tilt will be combined as a new sector. This can help satisfy the constraint of the number of available sectors in each BS, e.g., 3 or 6 sectors, and the 3D coverage scenario-based horizontal beamwidth requirements.

Step 2. Triangular prism coverage structure. Based on the triangle meshes generated in Step 1, the 2D triangular coverage cells are extended upward to a certain height H, thereby dividing the entire 3D space to be covered into several triangular prism coverage cells.

Step 3. Single triangular prism beam filling. Guided by the rule of antenna tilt tangent division, each triangular prism coverage cell is promptly partitioned into low, medium, and high layers, wherein the ranges of their heights have a correlation with the values of antenna tilt tangents. Incorporating 3D scenario-based beams, the three layers within a triangular prism coverage cell are covered by three BS sectors, respectively, and a hierarchical filling is thereby accomplished. Within each sector of the triangular prism coverage cells, signal coverage at a point is achieved only when the received signal power at the point exceeds a specified threshold.

Field test and results. Field test results indicate that given conditions that synchronization signal reference signal received power (SS-RSRP) is greater than −95 dBm, the signal coverage rate of 99% is achieved within a 3D space of 44 km^2 (area) × 300 m (height). Specifically, drone-borne test terminals navigate through the coverage space at a velocity of 15 m/s, holding altitudes of 100, 200, and 300 m, in turn. The sampling frequency of the test terminals is set to 5 Hz, resulting in a spatial sampling interval of 3 m. For each altitude setting, the sampling routes are configured in a grid-like formation, which enables the test terminals to span the entire planar area.

Despite the above ideal results, several limitations remain in G2A wireless coverage, which is also a direction worth further research.

Beam design. Beam design has become a key factor in wireless coverage. Traditional beam designs follow specific rules where the beams have greater width in the horizontal direction and smaller width in the vertical direction, thereby offering wide terrestrial coverage. Furthermore, beam design in vertical dimension has been taken into account in 5G massive multiple-input multiple-output (MIMO) systems. Aided by more flexible and accurate antennas, 17 scenario-based beams have been designed to enhance the coverage capability for the ultra-low-altitude area below 100 m. However, the scenario-based beam configuration for G2A wireless coverage scenarios is still in a vacant state. Specifically, the beam parameters such as beamwidth and antenna tilt of the TBSs need to be calculated and generated based on the scenario characteristics.

Interference management. G2A wireless coverage faces a greater challenge in interference management compared with terrestrial coverage. Traditional frequency multiplexing methods cannot be directly applied to G2A wireless coverage since the high overlap between beams will induce strong interference from neighbor TBSs, which significantly deteriorates the G2A coverage performance. Therefore, it is necessary to design a frequency resource allocation scheme suitable for G2A wireless coverage scenarios. With the help of cooperative multi-point transmission technique [5], the beams can be effectively managed. Specifically, the beams in each triangular prism will be divided into clusters for cooperative transmission. Accordingly, the impact of interference caused by complex beam relationships will be alleviated. Furthermore, the difficulty of frequency planning can be greatly reduced while the spectrum utilization can be maximized by adopting the three-coloring method for spectrum planning.

Energy efficient collaboration. Energy efficiency is also a critical consideration in G2A wireless coverage [6]. Compared to traditional terrestrial coverage, the addition of height as a dimension and the potential increase in sectors for each BS in the designed triangular prism coverage structure may lead to higher energy consumption. Therefore, energy efficiency optimization needs to be comprehensively considered while designing beam-filling methods. Specifically, considering the limitation of BS power, it is essential to maximize the average received signal power and throughput in the coverage area to achieve high-efficiency signal and capacity coverage.

Ground and air consistent coverage. In the evolution towards the 6G system, the majority of mobile users remain terrestrial users. Therefore, it is infeasible to devote all the TBSs to G2A coverage. Moreover, it is challenging to allocate additional sites for the construction of exclusive G2A coverage TBSs in typical urban scenarios. Hence, the key lies in maximizing the utilization of existing TBSs to achieve effective G2A coverage extension. Given the coverage requirements in 3D space, the first step is to determine the optimal proportion of G2A coverage TBSs. This ensures that the overall coverage rate of the entire 3D space is enhanced without compromising the experience of terrestrial users. Afterward, it is essential to select the optimal set of G2A coverage TBSs, especially the locations of TBSs, to achieve seamless coverage of the entire 3D space. Besides, if extra TBSs are required due to the insufficient ability of existing infrastructure, the number of additional TBSs and the impact of additional TBSs on terrestrial coverage performance should be minimized.

In summary, this study proposes a triangular prism-based 3D coverage structure and G2A coverage expansion method, including specific steps for coverage structure generation and beam filling. The effectiveness and superiority of the design are also validated by field test results. This study provides a paradigm of G2A coverage extension for future 6G systems.

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