# Design and Performance Analysis of Wireless Data Center Network Topology Comb

Qingfang Zhang, Jie Li, Zhijie Han, Xin He

*Abstract*—**This paper addresses challenges such as low connectivity and poor scalability in existing data center networks by adopting 60GHz millimeter-wave wireless communication technology and proposing a new wireless data center network topology called Comb. Firstly, the physical model of the wireless transmitter devices is presented, along with the construction process and algorithm for the Comb topology. Secondly, the necessary layers to avoid signal blocking and maximize the utilization of spatial resources are introduced. Then, the performance of the topology is analyzed, including the total number of connections between wireless transmitters on the same or different layers. Finally, experiments are conducted to evaluate the average degree of network nodes and the 1-hop node coverage. The results indicate that, at the same network scale, the Comb structure demonstrates improved connectivity.**

*Index Terms*—**Data center network, 60GHz, Topology design, Performance analysis**

## I. Introduction

In recent years, with the rapid development of internet technology and the digital transformation of society, the demand for large-scale data storage and processing has become increasingly urgent [1-4]. The emergence of data centers reflects the organization, standardization, and specialization of data processing and represents an important innovation in the development of information technology [5]. As the infrastructure supporting large-scale cloud computing services, data center networks have rapidly evolved, driven by their powerful data storage and processing capabilities, and their applications have permeated various aspects of social life. Traditional data center networks are based on wired designs [6] and typically follow a three-tier tree network architecture, with the bottom layer known as the access layer, the middle as the aggregation layer, and the top as the core layer. During the actual deployment of traditional data center networks, several issues arise, including complex wiring, susceptibility to errors, and maintenance difficulties [7-9].

In order to effectively address the drawbacks of traditional wired data centers, researchers have shifted their focus towards wireless communication technology [10-12]. The application of wireless communication technology in data centers not only overcomes the limitations of wired links but also brings various benefits. With the continuous increase in wireless devices and the expansion of wireless applications, the demand for wireless network transmission in modern society is steadily increasing. Currently, the use of millimeter-wave wireless communication technology is rapidly advancing, and the 60GHz frequency band also attracts researchers' attention. With the development of 60GHz millimeter-wave communication technology, this technology has gained recognition from many countries [13], and researchers have proposed its use in the construction of data center network topology [14,15].

Incorporating 60GHz millimeter-wave wireless communication technology [16] into the design of data center network topology to build flexible and reconfigurable data center networks is currently a research hotspot. Many researchers have proposed alleviating congestion in large-scale data center networks by using wireless communication technologies [17-19]. However, these solutions have some drawbacks, such as excessive reliance on ceilings installations, requiring precise alignment of signal receivers, and low penetration capability. These shortcomings can impede the development of wireless data centers. Designing efficient and reasonable network topology to meet the demands of data centers, such as high bandwidth, low latency, and strong scalability, is an urgent problem that needs to be addressed.

This paper addresses the challenges faced by data centers and the demands for scalability, bandwidth, and stability. Based on 60GHz millimeter-wave wireless communication technology, this paper proposes a novel wireless data center network topology named the Comb structure. By enhancing the transmission rates between nodes, this structure can effectively improve network connectivity and shorten routing paths. Our contributions are as follows:

- By taking advantage of the high transmission rate, strong anti-interference ability and directional characteristics of 60GHz millimeter-wave technology, this paper designs a wireless transmitter device. These devices enable omnidirectional data transmission without the

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Qingfang Zhang is a postgraduate student at the School of Computer and Information Engineering, Henan University, Kaifeng 475004, China. (e-mail: 104752190146@henu.edu.cn).

Jie Li is a professor at the School of Intelligent Engineering, Zhengzhou University of Aeronautics, Zhengzhou, 450046, China. (e-mail: jsjt9@henu.due.cn).

Zhijie Han is a professor at the School of Software, Henan University, Kaifeng 475004, China. (corresponding author, and e-mail: hanzhijie@126.com).

Xin He is a professor at the School of Software, Henan University, Kaifeng 475004, China. (e-mail: hexin@henu.edu.cn).

need for precise alignment between the antennas of two nodes.

- The paper provides the construction process and algorithms for the Comb topology. During the topology construction, to avoid signal interruption, the number of layers required to construct the topology structure is carefully determined. Additionally, in order to maximize the utilization of spatial resources, the height of each layer of wireless transmitter devices needs to be determined.
- The paper analyzes the performance of the Comb topology structure and calculates the total number of connections established between wireless transmitter devices on the same layer (or on different layers). Subsequently, experiments are carried out to demonstrate the average degree of network nodes and the node coverage within 1-*hop*. The results indicate that, under the same network scale, the Comb structure exhibits better connectivity.

The chapter settings of this paper are as follows. Chapter 2 discusses the existing technologies and application situations. Chapter 3 presents the construction process and algorithm of the Comb topology structure. Chapter 4 analyzes the properties of the Comb structure and then conducts experiments to demonstrate the degree of network nodes and 1-*hop* node coverage. Chapter 5 summarizes this paper.

## II. Related work

With the development of cloud computing technology, many applications require the support of a data center. Recently, the researcher's attention has been focused in building a novel wireless data center using wireless communication technology to address the massive and diverse data processing requirements.

Kandula et al. [15] proposed a structure called Flyways based on 60GHz high-frequency wireless technology, which adds wireless transmitters to existing infrastructure while keeping all wired links and network nodes in the original structure. According to the deployment requirements of the Flyways, three racks cannot be placed in a row, which would result in a chaotic topology layout. When some of the racks fail, maintenance and deployment also face serious challenges. This structure is difficult to meet the scalability and high fault tolerance requirements of Data Center Network (DCN).

Shihada et al. [20] proposed a wireless data center network structure, which uses 60GHz millimeter wave wireless communication technology to establish communication channels between racks by placing servers in cylindrical racks. This structure achieves full wireless connection between racks, which reduces the complexity of wiring. However, 60GHz millimeter wave wireless signals will rapidly decay due to the increase in transmission distance, and even small obstacles can affect their signal transmission, making the network unstable and requiring more expensive equipment and has low security. These wireless data center network structures ignore the relationships between topology, which results in a decrease in overall energy efficiency.

After that, Cui et al. [18] proposed Diamond, a new wireless data center network structure, which achieves wireless data transmission between racks by deploying wireless devices on servers in the rack. Furthermore, a 3D Ring Reflection Space (RRS) was proposed, which mainly includes key wireless technologies based on multiple reflections and precise reflections. These technologies fully utilize the 3D transmission space and greatly reduce interference during signal transmissions. However, the Diamond structure mainly focuses on how to reduce interference between wireless beams while neglecting how to improve wireless connectivity, which may lead to a decrease in the overall performance of the wireless data center network structure.

Chen et al. [21] proposed a wireless data center network structure called Graphite. The structure introduces a device with lifting and rotating arms that enables direct wireless communication between data center rack pairs by lifting the antenna to different heights and rotating it in the appropriate direction. However, this structure has a very obvious flaw, which is that when the racks in the topology structure are placed and the horn antennas are adjusted for height and direction. If one wants to expand the Graphite structure, one needs to reconfigure the height and direction of all antennas in the structure. The process of redeployment requires a significant amount of manpower and financial resources, and may also lead to a decrease in the flexibility of the entire network.

Existing studies indicate that current wireless data center network architectures commonly face limitations in transmission distance, connectivity, and scalability during practical deployment. To address these critical challenges and meet the evolving demands of wireless data centers, this paper proposes a novel wireless data center network topology, termed the Comb structure. This topology is constructed by integrating multiple basic network units, offering significant flexibility and scalability. First, based on the characteristics of 60 GHz millimeter-wave communication, a wireless transceiver is designed to facilitate data transmission between nodes. Subsequently, the paper systematically presents the construction method and corresponding algorithm for the Comb topology, along with key considerations during the construction process. Building on this, a theoretical analysis of the Comb topology's performance is conducted, deriving the total number of possible connections between nodes. Finally, experiments were conducted to evaluate the node degree and the 1-*hop* node coverage within the network. The results show that, under the same network scale, the Comb structure offers significantly better connectivity. The results indicate that, under the same network scale, the Comb structure demonstrates a significant advantage in terms of connectivity. In conclusion, the proposed Comb network topology effectively enhances the network connectivity, reduces routing path lengths, and improves the overall communication efficiency and stability of wireless data centers.

## III. The design of COMB topology

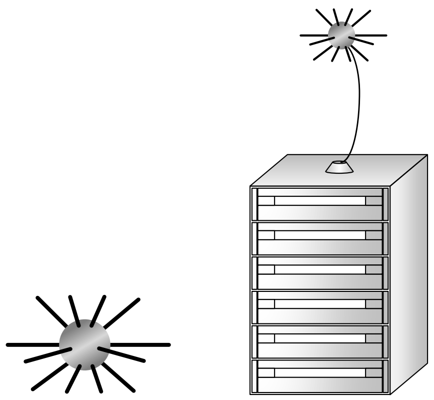
This chapter shows a wireless data center network topology based on 60GHz millimeter wave wireless communication. Combined with the characteristics of server rack, the physical model construction process of Comb is presented. Designing server racks based on 60GHz transmission characteristics and providing the physical model construction process for Comb.

*A. Structural design*

When building a wireless data center, we need appropriate base equipment for support. That is, according to the characteristics of the wireless data center network topology, base equipment suitable for this structure is designed to reduce equipment investment. In this structure, the design of the signal transmitter is mainly involved.

The signal transmitter is placed above the cabinet to transmit data. The cabinet is a container-like structure that encapsulates switches and servers interconnected by optical fiber. We connect the signal transmitter and the cabinet to transfer data.

The design of the signal transmitter is shown in Fig.1(a). According to its structure, the signal transmitter can be divided into two parts: a spherical base and an antenna. The spherical base can be divided into three layers, and on each layer, four small holes are evenly distributed for installing antennas. The signal transmitter can selectively install antennas according to its location to avoid wasting resources. Each spherical base is also equipped with a freely bendable and adjustable bracket for connecting the signal transmitter to the cabinet. As shown in Fig.1(b).



(a)signal transmitter (b)cabinet.

Fig. 1. Device structure diagram.

To help everyone better understand the composition of the signal transmitter, it will be defined using mathematical language below. As shown in Fig.2, it will be described in 3-dimensional Cartesian coordinates. Take the center of the signal transmitter as point $O$ to establish 3-dimensional Cartesian coordinates. To achieve full signal coverage, 12 antennas are installed on each signal transmitter. As shown in Fig.2, in the $xOy$ plane, taking the $Ox$ axis as the starting position, rotate counterclockwise and install the antennas at 45°, 135°, 225°, and 315° respectively. In the same principle, antennas are installed in the $yOz$ plane and $xOz$ plane in the same way. Finally, the schematic diagram of antenna installation on the signal transmitter is obtained as shown in Fig.2. To achieve full coverage, 3D MIMO technology is added, which can superimpose the signals of horizontal and vertical dimensions. Due to the addition of 3D MIMO technology [22-23], the coverage of the signal transmitter can be regarded as spherical full coverage. In this way, during data transmission, the accurate alignment of the antennas between the two nodes is no longer a strict standard.

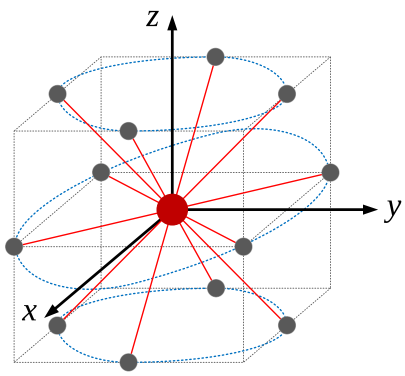
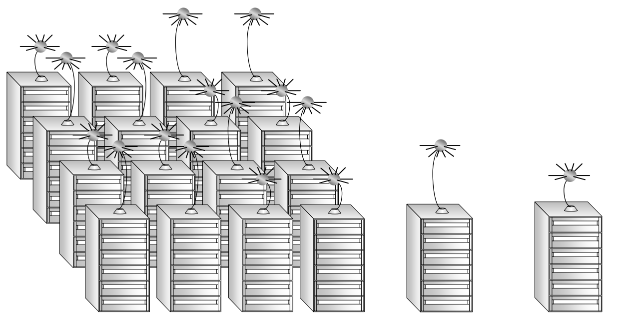



Fig. 2. Structure diagram of signal transmitter.

*B. Topological analysis*

Many factors need to be considered when arranging the cabinets. For example, the size of the cabinet itself, the height of the room, and the number of layers that the signal transmitters need to be arranged in order to avoid signal blocking. When the number of layers of signal transmitters is $l$, the performance of the wireless data center can be optimized. Considering the actual situation, when the position of the signal transmitter is different, the antenna arrangement will also change, as shown in Fig.3. Let the transmission distance of the signal transmitter in the topology be $R$, i.e., the transmission radius is $R$. The purpose of designing this wireless data center is to make all signal transmitters in the topology within the effective communication range and transmit data with other signal transmitters in the structure as much as possible.

As shown in Fig.3, a cabinet array of 4×4 is placed in a square area with a side length of $R$. In the constructed 2-layer topology, the horizontal and vertical distances between adjacent cabinets are $R/3$, and data transmission can be carried out between signal transmitters located on the same row (or column). In Fig.3, (a) is the overall effect diagram of the 2-layer topology viewed from the side above, (b) is the device diagram of the signal transmitter on the upper layer, and (c) is the device diagram on the lower layer.



(a)2-layer topology diagram (b)high layer (c) low layer

Fig. 3. Schematic diagram of signal transmitters.

The wireless data center network topology is constructed by placing signal transmitters on different layers. In order to facilitate understanding and description, the subsequent schematic diagram maps the topology to a 2-dimensional plane for description. As shown in Fig. 4, it is a 2-layer topology. In the figure, black dots represent signal transmitters on the upper layer and white dots represent those on the lower layer. This design is to ensure that no signal blocking will occur between any two nodes as long as the signal transmitter are within signal coverage. As shown in Fig.

4, it is a 2-layer topology arranged in a square area with side length of 2$R$. The signal transmitter located at the center of the area can communicate with up to 28 adjacent signal transmitters within the circular area whose radius is $R$.

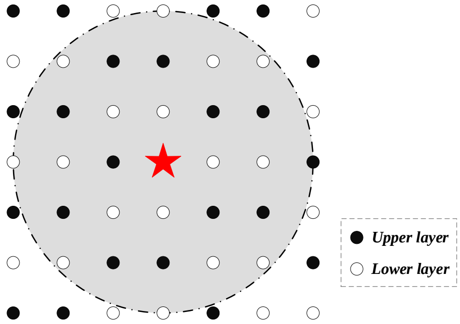
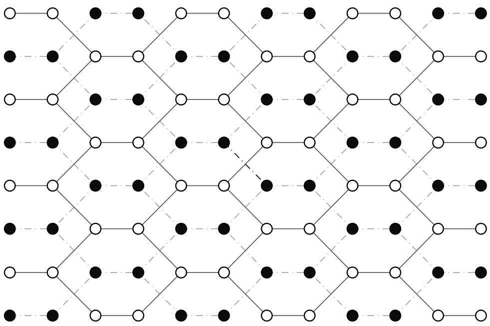
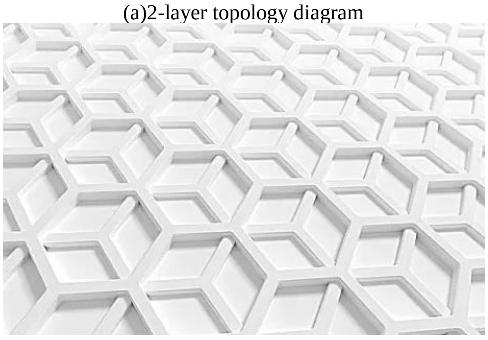



Fig. 4. Antenna signal coverage map.

As shown in Fig.5(a), it is a large network topology diagram formed by building multiple basic cell grids together. By observing Fig.5, it can be found that the network topology diagram is very similar to the Comb structure. This structure is formed by the staggered placement and combination of single-layer honeycomb structures, hence it is named Comb structure. With the increase of nodes and density in the data center, the multi-layer Comb structure is used to expand the data center, which can simplify the data center structure and make full use of resources.



(a)2-layer topology diagram



(b)Comb structure model

Fig. 5. 2-Comb structure diagram.

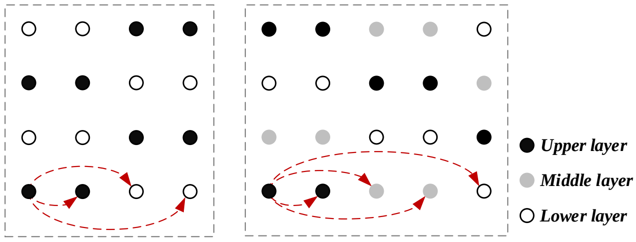
### *C. Construct topology*

*1.To avoid signal blocking, determine the number of layers required to build the topology.*

If a cabinet array of $m$×$n$ is built in a square area with side length $R$, an important factor to be considered is to leave enough space for signal transmitters in the same row (or column) but at different layers for communication. Where, $m$ represents the number of signal transmitters on each row in the area, and $n$ represents the number of signal transmitters on each column in the area. Since it is built in a square area with side length $R$, it is necessary to calculate the appropriate values of $m$ and $n$ to establish as many wireless connections as possible within the effective communication distance $R$. Let $\varphi$ and $\psi$ respectively represent the distance between adjacent signal transmitters in the same row or column, then $m \leq \lfloor R/\varphi \rfloor, n \leq \lfloor R/\psi \rfloor$.

According to the characteristics of the topology, while avoiding signal blocking, in the square area with side length $R$, a maximum of two signal transmitters on each row can be located on the same layer. Thus, the required number of layers is $\lceil m/2 \rceil$. Similarly, at most two signal transmitters on each column can be located on the same layer, so the required number of layers is $\lceil n/2 \rceil$. The larger value in $\{\lceil m/2 \rceil, \lceil n/2 \rceil\}$ should be taken as the number of layers, denoted as $l$, to build the topology. For ease of description, the number of layers $l$ is encoded from bottom to top.

For example, when $m$=4, $n$=4, the required number of layers is $\{\lceil m/2 \rceil, \lceil n/2 \rceil\}$=$\{\lceil 4/2 \rceil, \lceil 4/2 \rceil\}$=$\{2,2\}$=2 . The resulting topology is shown in Fig.6(a). When $m$=5, $n$=4, the required number of layers is $\{\lceil m/2 \rceil, \lceil n/2 \rceil\}$=$\{\lceil 5/2 \rceil, \lceil 4/2 \rceil\}$=$\{3,2\}$=3. The resulting topology is shown in Fig.6(b).




(a)$m$=4, $n$=4 (b)$m$=5, $n$=4

Fig. 6. Layer number diagram of topology.

*2.Maximize the utilization of space resources by determining the number of layers where each signal transmitter is located.*

It can be found from the schematic diagram in the previous chapter that the position of the signal transmitter in the topology changes circularly in rows and columns. In a row, every two signal transmitters change in high and low cycles together. In a column, there is a single high-low cycle change. For clear calculation of the position of each signal transmitter in the topology with the scale of $m \times n$, $h_{i,j}$ is used to represent the number of position layers of the signal transmitter. Thus, the number of position layers of the signal transmitter on row $j$ of column $i$ can be expressed as $h_{i,j}$=$(\lfloor j/l \rfloor \% l+i)\% l$ $(0 \leq i < m, 0 \leq j < n)$.

For example, in a 2-layer topology, when $l$=2, if you want to know the number of layers of the signal transmitter located in the 3$rd$ row of the 4$th$ column, as shown in Fig.7. When $i$=2, $j$=3, the number of layers of the signal transmitter is $h_{i,j}$=$(\lfloor 3/2 \rfloor \%2+2)\%2$=1 ⋯ 1. That is, the signal transmitter at this position is located in the lower layer.

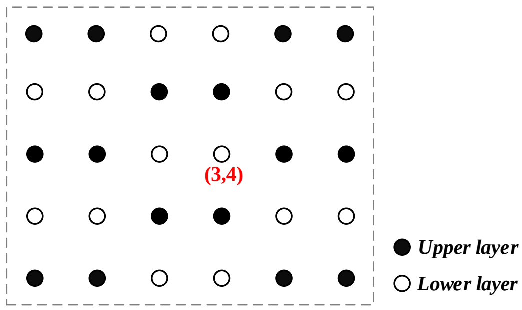



Fig. 7. Position layers of signal transmitter.

In a 3-layer topology, if you want to know the number of layers of the signal transmitter located in the $3rd$ row of the $6th$ column, as shown in Fig.8. When $i$=2, $j$=5, $h_{i,j}=(\lfloor 5/3\rfloor\%3+2)\%3=1\cdots 1$. That is, the signal transmitter at this position is located in the middle layer.

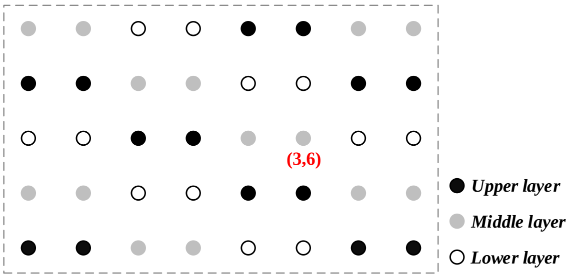


Fig. 8. Position layers of signal transmitter.

*3.The process of constructing network topology.*

To clearly show the construction process of Comb topology, Algorithm 1 is given. The following code is the construction algorithm of Comb topology.

**Algorithm 1**: Comb construction algorithm.

Input: $m, n$ ($m\times n$ cabinets).
Output: $l, h_{i,j}$.

$l=\max\{\lceil m/2\rceil, \lceil n/2\rceil\}$; // Take out the larger number from $\{\lceil m/2\rceil, \lceil n/2\rceil\}$
***for*** $j=0; j<n; j{+}{+}$;
***begin***
  ***for*** $i=0, i<m, i{+}{+}$;
    $h_{i,j}=(\lfloor j/l\rfloor\%l+i)\%l$;
  ***end***
***end***

Through the construction algorithm of Comb topology, the $l$-layer topology can be calculated. As shown in Fig.9, it is the topology diagram when $l=3$. However, it should be noted that in a square area, if the density between signal transmitters in the horizontal direction is too large, even if there is a large enough distance between signal transmitters in the vertical direction, it will require a large number of layers for construction. To enhance the scalability of the Comb wireless data center topology, this paper sets the maximum number of topology layers to 3. This design is based on two primary considerations: 1) in practical deployment environments, the floors of buildings that house server racks have fixed vertical spacing, which limits the efficient use of vertical space; 2) an excessive number of layers may constrain the flexibility of data center expansion and negatively impact communication performance and overall system efficiency. Due to the limitation of space height and to avoid such issues during the construction process, it is recommended to build a topology with a small number of layers.

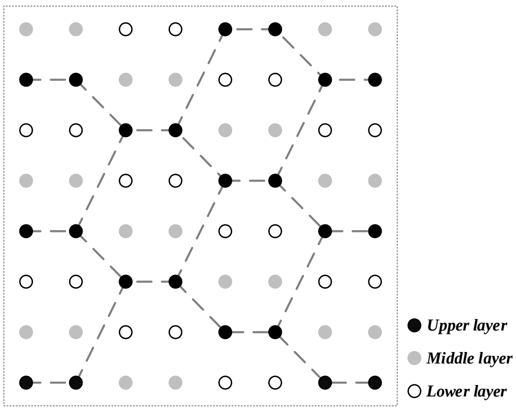


Fig. 9. 3-Comb topology diagram.

## IV. PERFORMANCE EVALUATION OF COMB STRUCTURE

### *A. Layer spacing*

In order to avoid signal blocking, wireless transmitters are deployed in different layers. It also needs to be considered that the length and thickness of the antenna itself on the wireless transmitter will also affect the signal transmission and then affect the distance between layers. The following will determine how to deploy the layer spacing according to the length and thickness of the antenna. For the convenience of discussion, the tentative diameter of the antenna is $d$.

It is known that the distance between adjacent layers should not be too small. Otherwise, when the signal is transmitted across layers, it will be blocked by the wireless transmitter in the middle layer, which will affect the signal transmission and further affect the performance of the data center. In the following discussion, $x\times y$ cabinets are arranged in a square area of $r\times r$. Any two cabinets in this area are within the signal range of 60GHz millimeter wave wireless communication. Here, let $R=\sqrt{(x\text{-}1)^2+(y\text{-}1)^2}$, and set $\tau=\max(x,y)$.

**Theorem 4.1** In the Comb topology, the layer spacing between the $l$-*th* layer and the ($l$-1)-*th* layer should meet the following formula

$$\left[\frac{2(\tau\text{-}2)^l\text{-}(\tau\text{-}1)}{(\tau\text{-}2)^2}+(\tau\text{-}2)^2\right]\times d\le\delta_l \tag{1}$$

In order to ensure the smooth transmission of the signal and determine the final layer spacing, two situations regarding the location of the wireless transmitter need to be discussed. The reasoning process is as follows:

*1.The wireless signal receiving device and the transmitting device are positioned on adjacent layers.*

In this case, if the distance between two adjacent layers is very small, the neighbor nodes on the same layer will interfere with the data transmission. In the topology, there are two consecutive nodes in the horizontal or vertical direction of the same layer, one of which needs to transmit with the other node in the adjacent layer. The worst case is that two nodes are at both ends of the area. If you want to communicate, you need to avoid $\tau$-2 wireless transmitters. If it is assumed to be in a 4×4 area, it is necessary to avoid $\tau$-2=4-2=2, as shown in Fig.10.

*2.The wireless signal must pass through multiple layers before reaching the receiving device.*

In addition to the above-mentioned signal transmission between adjacent layers to avoid the occurrence of signal blocking, we also need to consider the possible occurrence of signal blocking through the middle layer. In the worst case, $\tau$-2 wireless transmitters should also be avoided. Suppose the area is 6×6. The number to be avoided is $\tau$-2=6-2=4, as shown in Fig.11.

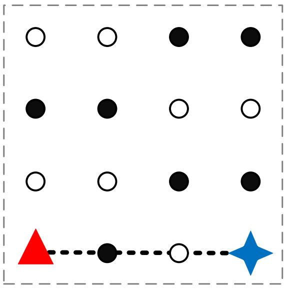


Fig. 10. Adjacent layers.

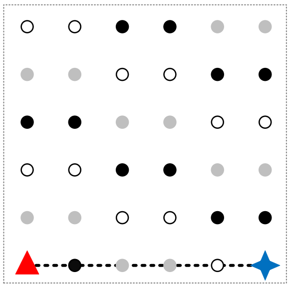


Fig. 11. Multiple layers.

According to the given theorem, we can summarize the number of floors and the range limit of Comb structure, and further calculate the space from the lowest floor to the highest floor. Considering the practical constraints of data centers and the design characteristics of the Comb structure, the inter-layer spacing should not be excessively large, mainly due to two reasons: 1) in many data centers, the distance from the top of a server rack to the ceiling typically ranges from 2*m* to 4*m* and often does not exceed 4*m*. To ensure the flexibility and broad applicability of the Comb structure, its spatial requirements should align with common data center configurations; 2) the Comb design relies on wireless transmitters placed at different vertical levels for inter-node communication. If the room height is too large, transmitters on the topmost layer would require extended mounting structures, which increases the risk of mechanical instability and complicates deployment and maintenance.

To facilitate deployment, set the height to 4*m*. Assuming that the width *d* of the wireless transmitter is 3.5*cm*, it can be calculated according to the formula that 100 devices can be deployed in a square area of side length 10*m*, and the Comb structure can deploy at most 3 layers.

According to the knowledge of graph theory, the entire data center is represented by the graph model $G=(V,E)$.

1) Vertex Set: $V=\{\quad\}$. It is the set of cabinets equipped with wireless transmitters in the entire network.

2) Edge *Set:* $V=\{\quad\}$. It is the set of signal transmission connections that can be established between pairs of cabinets in the entire network.

In order to describe the connectivity of the Comb structure, two indicators, $\omega$ and $\Delta$, are selected for measurement. $\omega$ is the average degree of nodes in the network and is expressed as $\omega=\frac{\sum_{v\in V}(v)}{|V|}$. $\Delta$ represents the proportion of cabinets that can directly transmit data with the central cabinet within the range of 60GHz millimeter wave communication and is expressed as $\Delta=\frac{|(v,v')|dist(v,v')<R}{|V|}$. Here, $v$ refers to any point in the square area (excluding nodes on the boundary). $(v,v')$ refers to the wireless connection for data transmission, and $\mathrm{dist}(v,v')$ refers to the horizontal distance between node $v$ and $v'$. The purpose of this selection is to avoid the boundary effect where the average degree of nodes on the boundary is less than that in the central area due to structural constraints. From the node average degree formula, the following theorem can be deduced: $\omega=\frac{\sum_{v\in V}(v)}{|V|}$.

**Theorem 4.2** In $G=(V,E)$, the average degree $\omega$ of nodes can be calculated by the following expression

$$\omega=\frac{2|E|}{|V|} \tag{2}$$

According to the above formula and conditions, it can be concluded that the larger the parameters $\omega$ and $\Delta$ are, the more nodes around a given node can transmit data with it, indicating better connectivity of the network. Next, the average degree $\omega$ of nodes is analyzed in detail to prove that the Comb structure has superior and effective connectivity. Before this, a theorem is given, which is more convenient for the following proof work. According to the above assumptions, the total number of nodes in the whole network is $|V|=x\times y$. If we want to calculate the average degree $\omega$ of nodes in the whole network, we need to obtain the total number of edges in $G$.

### B. Performance analysis

To highlight the good connectivity and superior performance of the Comb structure, a comparative analysis of the performance of the Flyways structure and the Graphite structure is provided below.

*Performance Analysis of the Flyways*

Let graph $G_{Fly}$ represent the Flyways structure. The size of graph $G_{Fly}$ is calculated below.

**Theorem 4.3** In the Flyways structure, the total number of edges in graph $G_{Fly}$ is

$$|E_{Fly}|=(x\text{-}1)[(3u+1)(y\text{-}1)\text{-}(u+1)^2]+(x\text{-}1)(y\text{-}1) \tag{3}$$

Where, $u=\left\lfloor\sqrt{R^2\text{-}w_1^2}/(l+1)\right\rfloor$.

Due to the limitations of 60GHz millimeter-wave characteristics, wireless connections for data transmission can only be established between adjacent cabinets in the same row or between adjacent rows if they are within communication range. Assuming the distance from the top of the cabinet to the ceiling is $w_1=3.5m$. Therefore, we will discuss all edges in the edge set $|E_{Fly}|$ of the Flyways structure in two cases.

1) The wireless signal receiver and transmitter are on the same row. The two signal transmitters used for signal transmission are in adjacent positions. Between each pair of adjacent cabinets in a row, $(x\text{-}1)$ pairs of data transmission connections can be established. The total number of these connections is $(x\text{-}1)(y\text{-}1)$.

2) The wireless signal receiver and transmitter are on adjacent rows. Select a node from the vertex set $V_{Fly}$. Under the constraint of the 60GHz millimeter-wave transmission range, this node can establish wireless data transmission connections with cabinets in adjacent rows. The total number of these connections is $(x\text{-}1)[(3u+1)(y\text{-}1)\text{-}(u+1)^2]$.

By applying Theorem 4.2 to calculate the average node degree in the Flyways structure, the following theorem is obtained

**Theorem 4.4** In the Flyways structure, the average node degree is

$$|\omega_{Fly}|=2\left(1\text{-}\frac{1}{x\text{-}1}\right)\left[(2u+1)\text{-}\frac{u(u\text{-}1)}{y\text{-}1}\right]+2\left(1\text{-}\frac{1}{y\text{-}1}\right) \tag{4}$$

*Performance Analysis of the Graphite*

Similar to the previous section, let graph $G_{Grap}$ represent the Graphite structure. The size of the entire graph $G_{Grap}$ is calculated as follows.

**Theorem 4.5** In the Graphite structure, the total number of edges in graph $G_{Grap}$ is

$$|E_{Grap}|=\sum_{i=1}^{2}(x\text{-}i)[(2u_i+1)(y\text{-}1)\text{-}u_i(u_i+1)]+\frac{1}{2}(x\text{-}1)(y\text{-}1) \quad (5)$$

Where, $u_1=\left\lfloor\sqrt{R^2\text{-}w_2^2}/(l+1)\right\rfloor$, $u_2=\left\lfloor\sqrt{R^2\text{-}4w_2^2}/(l+1)\right\rfloor$.

The main difference between the Graphite structure and the Flyways structure is that in the Graphite structure, the signal transmitters are located on different layers, which allows for more wireless connections. Assuming the distance between signal transmitters at the highest and lowest positions in the vertical direction is $w_2$=3.5$m$, we will discuss all edges in the edge set $E_{Grap}$ of the Graphite structure in three cases.

1) The wireless signal receiver and transmitter are on the same row. In the Graphite structure, the positions of signal transmitters on the same row are also varied, as they are distributed across different layers. At most, there are 2 signal transmitters on the same layer, with a similar distribution across other layers. Therefore, the number of connections that can be established in this case is $\frac{1}{2}(x\text{-}1)(y\text{-}1)$.

2) The wireless signal receiver and transmitter are on adjacent rows. In this case, as long as the two nodes involved in data transmission are within the 60GHz millimeter-wave transmission range, a wireless connection can be established between them. Therefore, the number of connections that can be established in this case is $(x\text{-}1)[(2u_1+1)(y\text{-}1)\text{-}u_1(u_1+1)]$.

3) The wireless signal receiver and transmitter are on different rows. In this case, for data transmission between the two nodes, they need to span one or more intermediate rows, and if both nodes are within the transmission range, a wireless connection can be established between them. Therefore, the number of connections that can be established in this case is $(x\text{-}1)[(2u_2+1)(y\text{-}1)\text{-}u_2(u_2+1)]$.

By applying Theorem 4.2 to calculate the average node degree in the Graphite structure, the following theorem is obtained.

**Theorem 4.6** In the Graphite structure, the average node degree is

$$|\omega_{Grap}|=\sum_{i=1}^{2}(1+i)\left(1\text{-}\frac{i}{x\text{-}1}\right)\left[(2u_i+1)\text{-}\frac{u_i(u_i+1)}{y\text{-}1}\right]\text{-}1 \quad (6)$$

*Performance Analysis of the Comb*

In this section, a 2-layer Comb structure is used as an example to prove the advantages of this design by calculating its connectivity. To facilitate the following proof, let $G_{Comb}$ represent the graph model corresponding to the Comb structure.

**Theorem 4.7** In the 2-layer Comb structure, the sum of the edge numbers $|E_{Comb}|$ in $G_{Comb}$ is

$$\begin{aligned}|E_{Comb}|=&x(y\text{-}2)+\frac{1}{2}(x\text{-}1)[(2u+1)y\text{-}(u+1)]+\frac{1}{2}x\\&+\frac{1}{2}\sum_{i=1}^{2}\frac{1+i}{2}(x\text{-}i)[(2\lambda\text{-}1)(y\text{-}1)\text{-}(\lambda_i+1)^2]\text{-}\frac{1}{4}(x\text{-}1)(y\text{-}1)\end{aligned} \quad (7)$$

Where, $u=\left\lfloor\sqrt{R^2\text{-}w_3^2}/(l+1)\right\rfloor$, $\lambda_1=\left\lfloor\sqrt{R'^2\text{-}w_3^2}/(l+1)\right\rfloor$, $\lambda_2=\left\lfloor\sqrt{R'^2\text{-}4w_3^2}/(l+1)\right\rfloor$, $R=\sqrt{R^2\text{-}h_2^2}$.

Because in the Comb structure, the transmitter can be deployed in the same layer or in different layers, the total number of edges in the topology should be calculated according to these two different transmission situations. Here, the distance between the wireless transmitters on the highest layer and the lowest layer is 3.5m and is denoted as $w_3$.

*1.The wireless signal receiving device and the transmitting device are positioned on adjacent layers.*

When the wireless transmitter is on the same layer, it can be seen from the structural characteristics of the Comb that the two nodes of wireless connection can be on the same line, adjacent line or diagonal of a similar hexagon. The following three scenarios are discussed respectively.

1) When the wireless connections are in the same row, the wireless signal receiving end and transmitting end building them are also in the same row. The total number of wireless connections between adjacent cabinets is $x(y\text{-}2)$. In the 4×4 2-Comb structure as shown in Fig.12, the total number of wireless connections is $x(y\text{-}2)=4\times2=8$.

2) The wireless connection is constructed by nodes on a diagonal similar to that of a hexagon. In this case, the number of wireless connections established in the Comb structure is $\frac{1}{2}xy$. As shown in Fig.13, the total number of connections is $\frac{1}{2}xy=\frac{1}{2}\times4\times4=8$.

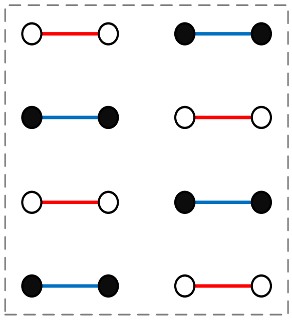


Fig. 12. On the same line

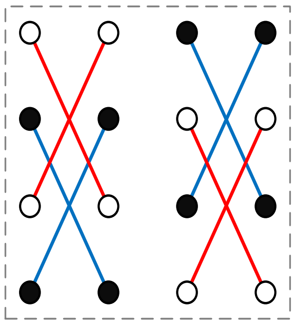


Fig. 13. On the diagonal

3) The wireless connection is constructed by two nodes on adjacent rows and columns. And in this case, the number of wireless connections established in the Comb structure is $\frac{1}{2}(x\text{-}1)[(2u+1)y\text{-}(u+1)]$. As shown in Fig.14, if a parameter $u$=3 is introduced as above, then the total number of wireless connections is $\frac{1}{2}(x\text{-}1)[(2u+1)y\text{-}(u+1)]=\frac{1}{2}\times3\times[(2\times3+1)\times4\text{-}(3+1)]=36$.

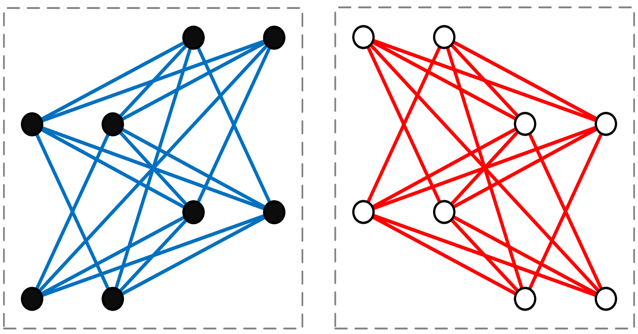


Fig. 14. On adjacent rows and columns

Based on the above three conditions, it can be concluded that in the following conditions, the total number of wireless connections constructed is

$$x(y\text{-}2)+\frac{1}{2}(x\text{-}1)[(2u+1)y\text{-}(u+1)]+\frac{1}{2}xy \quad (8)$$

Where, $u=\left\lfloor\sqrt{R^2\text{-}w_3^2}/(l+1)\right\rfloor$.

*2.The wireless connection is established between different layers.*

Here, $h_1$ is used to represent the distance from the first floor to the top of the cabinet, and $h_2$ is used to represent the distance from the second floor to the top of the cabinet. The distance between the first floor and the second floor is $h_2$-$h_1$. For the convenience of calculation, the height from the first floor to the top of the cabinet is temporarily ignored, $h_1$=0. So here, $h_2$ is used to represent the layer spacing between the first layer and the second layer. In this way, the actual effective transmission distance of 60GHz millimeter wave in the Comb structure is $R'=\sqrt{R^2\text{-}h_2^2}$. Therefore, in the 2-layer Comb structure, the sum of the number of wireless connections between different layers is

$$\frac{1}{2}\sum_{i=1}^{2}\frac{1+i}{2}(x\text{-}i)[(2\lambda_i\text{-}1)(y\text{-}1)\text{-}(\lambda_i+1)^2]\text{-}\frac{1}{4}(x\text{-}1)(y\text{-}1) \tag{9}$$

Where, $\lambda_1=\left\lfloor\sqrt{R'^2\text{-}w_3^2}/(l+1)\right\rfloor$, $\lambda_2=\left\lfloor\sqrt{R'^2\text{-}4w_3^2}/(l+1)\right\rfloor$, $R'=\sqrt{R^2\text{-}h_2^2}$.

The total number of wireless connections constructed in the Comb structure can be obtained by summing up all the wireless connections generated in all the aforementioned situations.

Finally, taking Theorem 4.2 as the basis, we can calculate the average degree of nodes in the 2-layer Comb structure.

**Theorem 4.8** The average degree of nodes in the 2-layer Comb topology is

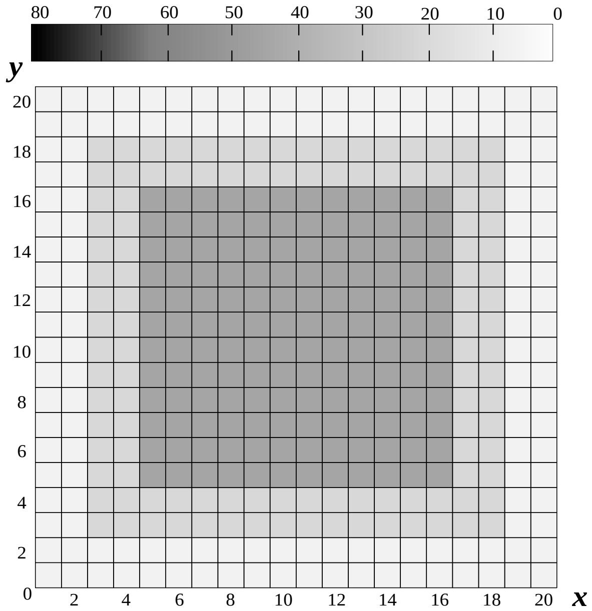
$$\begin{aligned}\omega_{Comb}=&\sum_{i=1}^{2}\frac{1+i}{w_3}\left(1\text{-}\frac{i}{y-1}\right)\left[(2\lambda_i+1)\text{-}\frac{\lambda_i(\lambda_i+1)}{x\text{-}1}\right]\\&+\left(1\text{-}\frac{1}{y\text{-}1}\right)\left[(2u+1)\text{-}\frac{u(u+1)}{x\text{-}1}\right]\end{aligned} \tag{10}$$

*C. Experiment and performance evaluation*

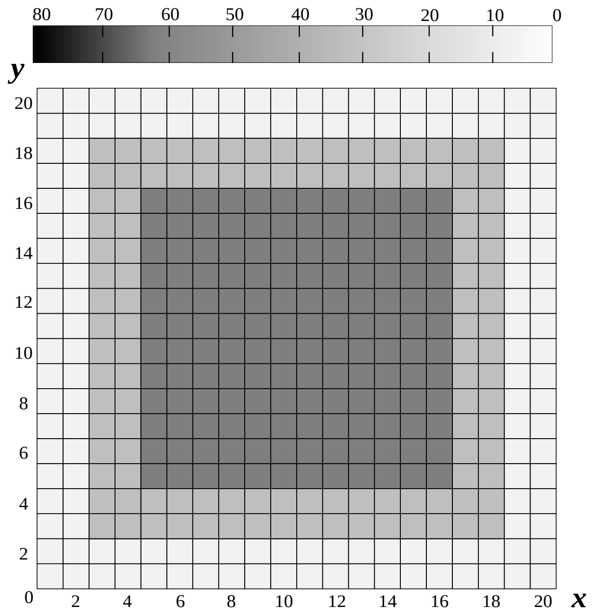
In order to show the superiority of the performance of the Comb structure, the performance of the Comb structure is compared with that of the Flyways structure and the Graphite structure. During the experiment, the effective communication range of 60GHz millimeter wave is set to 10*m*, and the scale is changed from 20×20 to 40×40. In order to measure the performance of the Comb structure among the three structures when the cabinet density is different, and for the convenience of the next experiment, set the distance between the top of the cabinet and the roof as 3*m*, and set the distance between the wireless transmitters on the top of adjacent row or column cabinets to be 2*m*, increasing by 0.5*m* each time until 5*m*.

*Degree of network node*

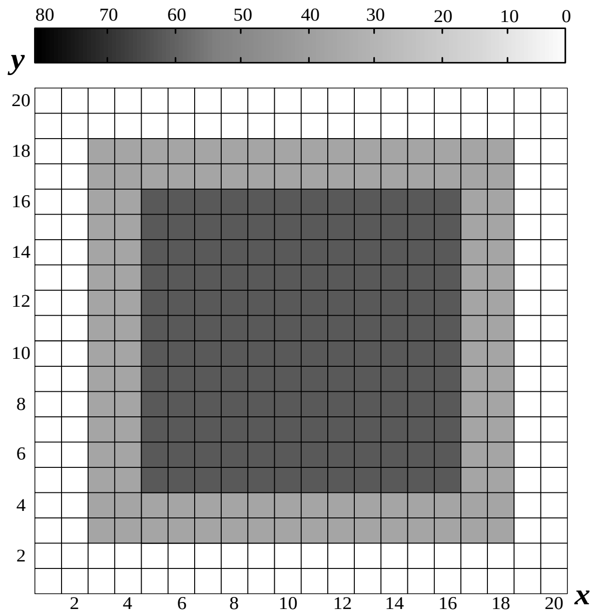
The degree of nodes in a data center network is an important index to measure the communication ability of a node. This index indicates the number of nodes that can establish wireless connection between the receiving end and the transmitting end within the effective communication range of 60GHz millimeter wave. If the degree of nodes in the network is high, it can be considered that a node has high flexibility. It can establish more network flows with other nodes in the network, and further improve the performance of the whole network. As shown in Fig.15, the hotspot map is used to define the distribution of the three structural points.



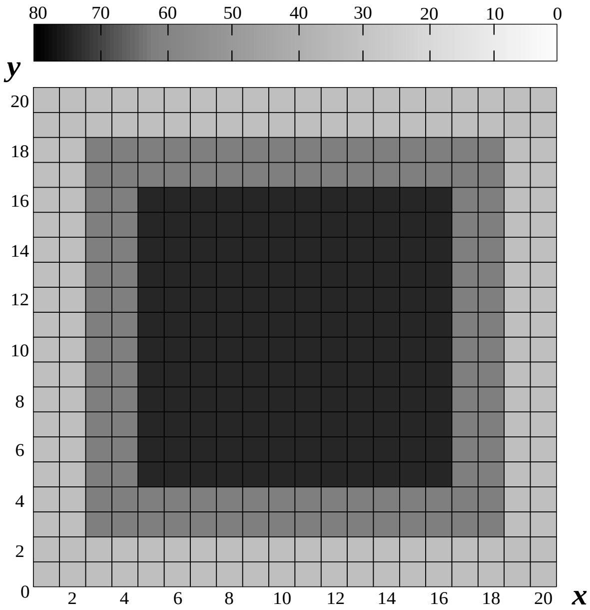
(a)Flyways



(b)Graphite



(c)2-Comb

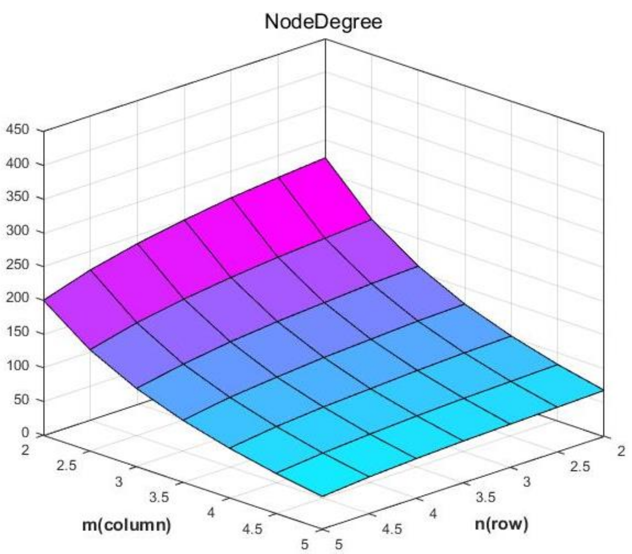



(d)3-Comb

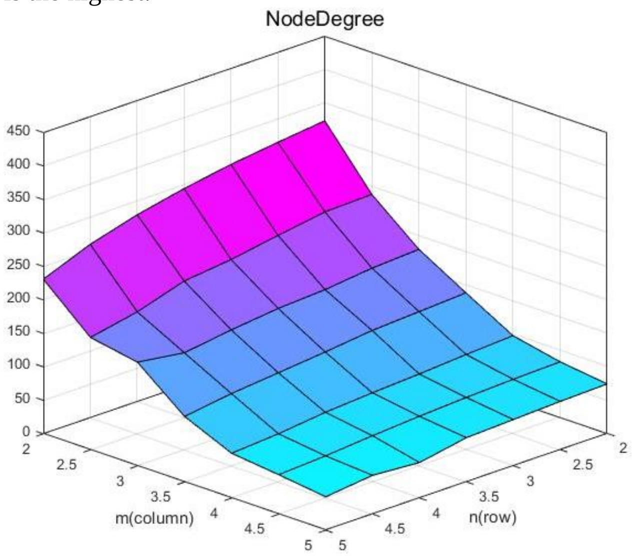
Fig. 15. Network hotspot map.

In order to prove that the Comb structure can effectively handle signal blocking even when the number of deployment layers does not meet the algorithm requirements. Looking at Fig.15, we can see that when the node is in the center of the structure, the node degree of the Comb structure is higher than that of the Flyways structure and the Graphite structure. In other words, the Comb structure can provide more opportunities for wireless transmission in the wireless data center. It should be noted that the degree of nodes on the edge is smaller than that of center nodes, which is called boundary effect. However, when the network scale is large enough, the boundary effect can be ignored, and only the degree of nodes in the central area needs to be paid attention to.

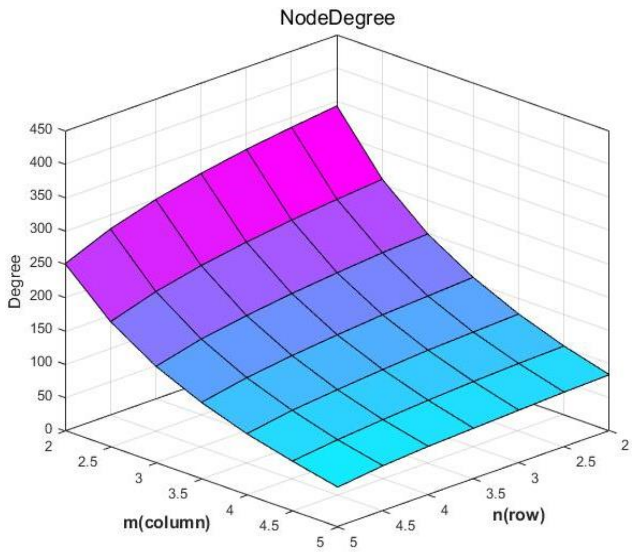
The degree of nodes in the center area of the Flyways structure, the Graphite structure and the Comb structure is calculated here. The distance between the cabinets in horizontal and vertical directions is increased uniformly from 2$m$ to 5$m$. According to the different density, the layer number of the Comb topology is mainly selected by the degree of nodes in the center area. When the density of network nodes is low, a 2-layer structure is usually selected, and when the density is high, a 3-layer structure or even a 4-layer structure should be selected. The experimental results are shown in Fig.16. Observing the experimental results, it can be found that the degree of nodes in the Comb structure is the highest.



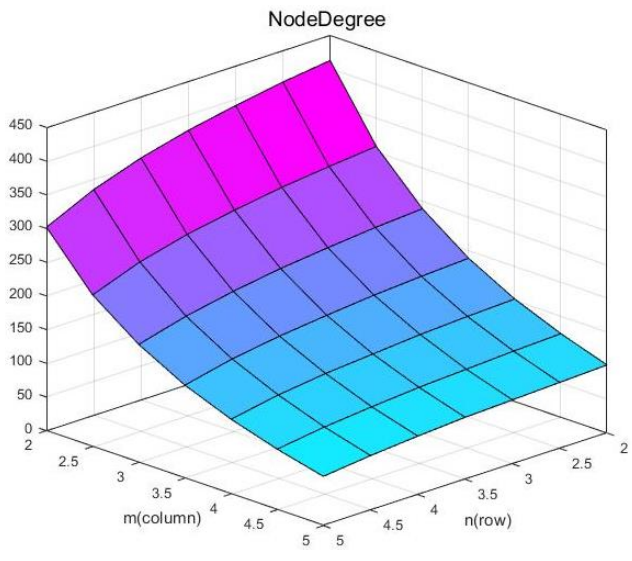

(a)Flyways




(b)Graphite




(c)2-Comb




(d)3-Comb

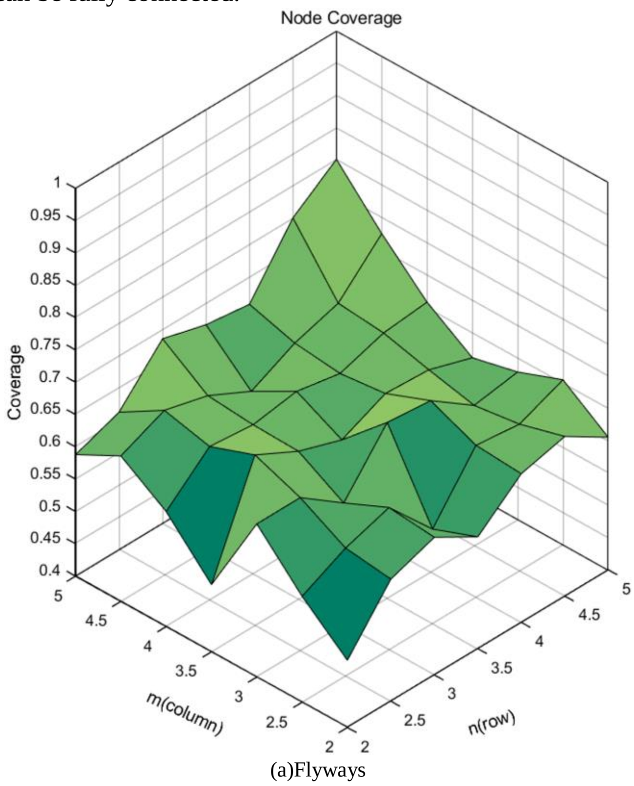
Fig. 16. Degree of Nodes.

As the scale of Comb wireless data center networks continues to grow, ensuring efficient and reliable communication between nodes becomes increasingly critical. A higher node degree generally indicates stronger communication capabilities. Analysis of the node degree in different topological structures reveals that the 2-Comb is more suitable for scenarios with lower rack density, while the 3-Comb is preferable under higher rack density. Experimental results show that the Comb topology consistently achieves the highest node degree, thereby providing the system with enhanced communication capacity.

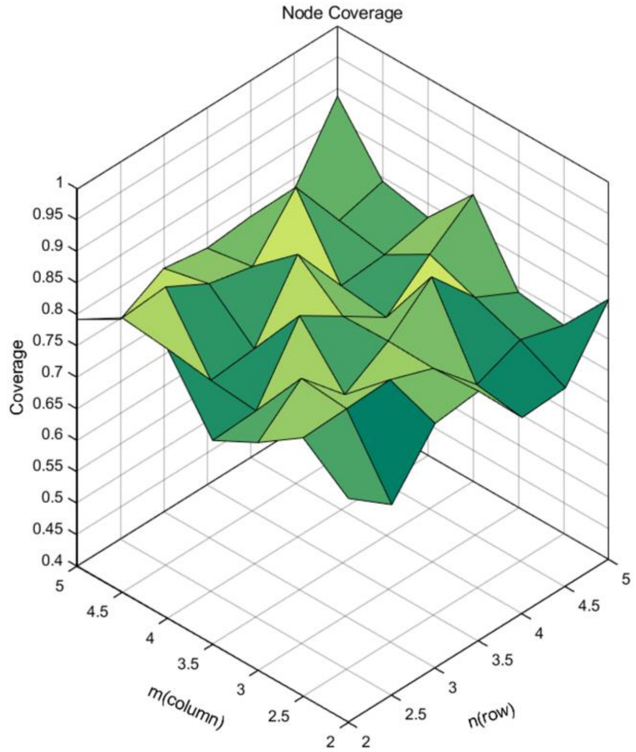
*Node coverage in 1-hop*

The 60GHz millimeter wave has a strong directionality. If there is a barrier between the transmitter and the receiver in its effective communication range, the wireless connection between them cannot be established effectively. Therefore, the node coverage in 1-*hop* is defined as the ratio of the number of nodes that can be directly connected to the sender to the total number of nodes in the square area. The node coverage in 1-*hop* is a measure of deploying cabinets and antennas in the network topology to reduce the occurrence of signal blocking. In other words, the higher the node coverage in 1-*hop*, the lower the probability of signal blocking. The ideal state is that when the node coverage is 100%, in the effective communication range, the nodes in the whole network can be fully connected.

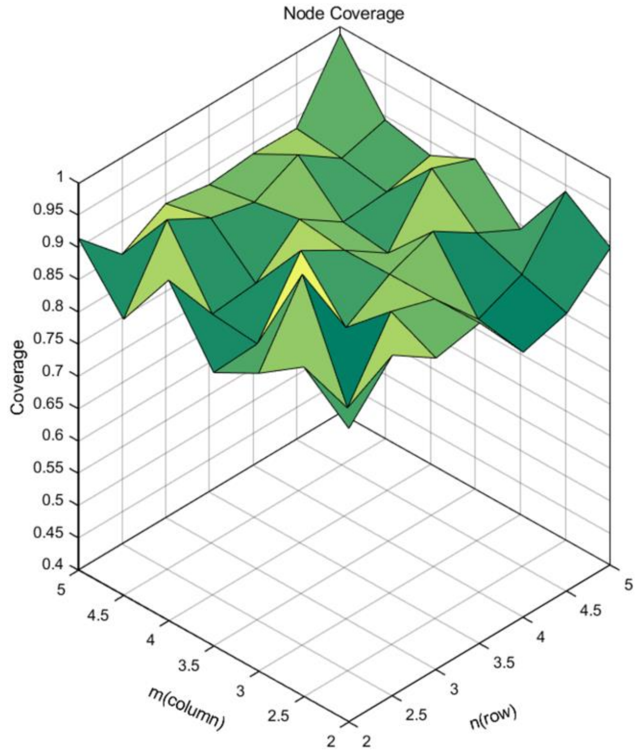
As shown in Fig.17, this is the coverage diagram of the Flyways structure, the Graphite structure, and the Comb structure in 1-*hop*. In relatively sparse networks, the highest node coverage of the Flyways structure in 1-*hop* is only 80%, and that of the Graphite structure is 88%. In contrast, the Comb structure has a higher node coverage in 1-*hop* and can even reach 100% in a sparse network. Within the effective communication range of 60GHz millimeter wave, the nodes can be fully connected.




(a)Flyways




(b)Graphite




(c)Comb

Fig. 17. Node coverage in 1-*hop*.

Through experiments, the network node degree and 1-*hop* node coverage of the Flyways structure, the Graphite structure and the Comb structure are analyzed respectively, thus proving that the Comb structure has better connectivity. Through the combination of theoretical analysis and experiment, it is fully demonstrated that the performance of the Comb structure is better than that of the Flyways structure and the Graphite structure.

## V. Conclusions

Cloud computing requires a lot of data computing support, and the data center provides basic hardware or computing support for cloud computing. In this paper, a new type of wireless data center, the Comb, is designed to solve the problems of the traditional wired data center, such as the complexity of wiring and the difficulty of scalability. The Comb solves the problem of multi-hop in data transmission to a large extent. The arrangement of cabinets in the Comb is designed according to grid shape, which is more conducive to deployment. Through the theoretical analysis of the properties of the Comb structure and experiments, the results show that the data transmission ability of the nodes in the Comb structure is strong, the average degree of the nodes is high, and the node coverage is large. However, in practical application, the network topology of the Comb wireless data center will be affected and limited by some external factors, such as the height of the cabinet itself, heat dissipation and other factors. When the structure is deployed and expanded, the number of building layers will be limited. Therefore, in the next research work, we need to further optimize the structure to achieve performance optimization.

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