VTRNet: A Design Method for a Hybrid Data Center Network Structure Supporting Visible Light Communication

Ying Du, Yaru Li, Pu Cheng, Hui Li, Weibei Fan, Roshan Kumar

Abstract—**With the rapid advancement of cloud computing, integrating wireless communication technology into data center networks has become particularly crucial. In this paper, we propose a hybrid data center network named VTRNet, which integrates the fusion of visible light communication technology with wired infrastructure, addressing the challenges of complex wiring, limited calability, and maintenance difficulties associated with the RRect architecture. Our construction approach consists of two steps: (a) placing racks on grid points according to encoding rules and installing four LED transceivers for each rack to establish a regular link structure; (b) Leveraging the characteristics of wireless small-world networks, using Euclidean distance and average clustering coefficient to create random links, thereby forming the wireless network structure. Secondly, based on the topological properties of the hybrid structure, we design a hybrid routing algorithm and analyze the topological characteristics of the VTRNet architecture. Finally, a series of experiments is conducted to evaluate the performance of the VTRNet architecture. The experimental results indicate that VTRNet enhances routing diversity, reduces the average path length, and significantly improves overall communication efficiency.**

Index Terms—**Wireless Data Center Networks, Visible Light Communication, Hybrid Structure, Hybrid Routing Algorithm.**

I. Introduction

WITH the swift evolution of the Internet, cloud computing technology has garnered increasing attention and plays an increasingly crucial role in the digital economy. Cloud computing technology enables remote access to computing and storage resources and is extensively utilized in the applications of companies such as Google and Microsoft [1]. Simultaneously, it provides users with a reliable and dynamic computing environment, offering flexible solutions for diverse business requirements. The cloud computing service model comprises software as a service (SaaS), platform as a service (PaaS), and infrastructure as a service (IaaS). As the core and infrastructure in the evolution of cloud computing, the data center offers services for distributed computing. In this intricate system, the data center is composed of numerous nodes, servers, and switches.

In recent years, the growing demand for emerging services has posed challenges to the scalability and reliability of data center structures. Due to the high traffic between the upper and lower layers of the traditional multi-tree structure, the switch utilization at the edge layer is low, leading to bandwidth bottlenecks. Furthermore, when switches in the core layer fail, a significant number of nodes also fail, leading to a single point of failure. Hence, researchers are committed to crafting a more realistic network topology to improve the performance and reliability of data centers. Notable examples include switch-centric architectures like Fat-Tree [2], VL2 [3], and server-centric designs such as BCube [4], DCell [5], and CSDC [6]. Despite substantial progress in Data Center Networks (DCNs) over the past decade, there are still lingering issues and challenges to be addressed. For instance, at certain times, specific switches or servers may handle disproportionately high traffic, and when the potential traffic exceeds the link capacity, it can result in excessive subscription or unbalanced traffic on specific links, leading to hot spots [7]. The traditional structure faces challenges in meeting expansion demands due to its inherent symmetry. To accommodate the growing service demand, the structure must exhibit robust scalability, achieved through horizontal extension utilizing cost-effective small commercial switches. The deployment and subsequent maintenance of the system require significant human and material resources due to the extensive use of wired links. The wiring for the wired links is intricate, and once the structure is established, it cannot be easily or frequently altered. In the contemporary landscape of data centers, ensuring the security of information transmission and storage is crucial. During data transmission, measures must be implemented to prevent data leakage and ensure data security. Additionally, due to the complex wiring and inflexible structure, effectively addressing hot spot congestion becomes a challenge. At the same time, in large-scale deployments, the centralized arrangement of numerous cables and server racks significantly reduces cooling efficiency. Therefore, there is a pressing need to explore more resilient and adaptable network architectures capable

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of overcoming these limitations.

In light of the issues inherent in the aforementioned wired structure, researchers have proposed the solution of a wireless data center. The rapid advancement of information technology has driven the development of domains such as cloud computing, artificial intelligence, and big data analysis, creating increasingly urgent demands for large-scale data storage and efficient processing. In this context, wireless data center network architectures have emerged, offering users convenient, fast, and reliable data storage and processing services. Currently, wireless communication technologies primarily include 60 GHz millimeter-wave and free-space optical communication technologies [8]. The integration of wireless communication technology with Data Center Networks (DCN) presents a promising avenue for innovation. Some researchers have integrated wireless communication technologies into data center networks (DCNs) to deploy wireless links between nodes with frequent communication, providing an effective solution to the congestion problem of hotspot [9], [10]. Recent work also explores hybrid approaches that utilize beamforming and optical techniques, such as the use of Airy beams to mitigate blockage issues and improve link efficiency [11]. However, these innovative integrations face a series of challenges. For instance, to avoid link blockage, certain schemes heavily rely on ceiling mirror reflections, require precise signal receiver alignment, exhibit limited scalability, and suffer from low penetration capability. Although these integrated solutions open up new possibilities for data center networks, in practical applications, we need to holistically consider and address these complex and diverse challenges. In the case of millimeter-wave communication and free-space optical communication, several technical and application-related issues arise, including limited spectrum resources, relatively low bandwidth utilization, high energy consumption, and the potential risk that lasers may pose to human health. Additional research focuses on FPGA-based visible light systems to address these concerns and improve bandwidth and stability [12]. Furthermore, traditional wired structures also face challenges in the practical scenarios described above.

To effectively address the challenges mentioned above, this paper proposes a hybrid design approach for data center networks that supports visible light communication (VLC). This approach is based on LED-enabled VLC and employs wireless links to construct the network architecture at the rack level. In comparison to traditional schemes, it eliminates the need for ceiling mirror reflection, thereby simplifying the deployment of wireless devices and improving scalability. With the advancement of visible light communication (VLC) technology, VLC offers a high transmission rate, uses light for data transmission, and provides a certain level of security. In this context, '1' signifies the presence of light, while '0' denotes the absence of light. The light-emitting diode (LED) used in VLC is economical, offers a long operational life, and is relatively straightforward to deploy and maintain [13]. Therefore, the integration of VLC into traditional wired data center networks is both feasible and effective, ultimately yielding notable performance improvements. The main contributions of this paper are summarized as follows:

- Based on the characteristics of low power consumption, high security, and easy deployment of VLC, the wireless topology is designed at the rack level. A hybrid topology named VTRNet is constructed by integrating this wireless topology with the wired topology.
- Based on coding rules and average clustering coefficients, a wireless structural connection mode and a hybrid routing algorithm are designed.
- The topological properties of VTRNet are analyzed, and experiments are conducted to assess its performance.

This article proceeds as follows: Section 2 provides an overview of the current classification of DCN. Section 3 details the structure construction method and the hybrid routing algorithm. In Section 4, the relevant property analysis and experiments are presented. Finally, Section 5 concludes the paper.

II. Related Work

Although current data center network architectures are rapidly evolving, several challenges still need to be addressed. The following section outlines the classification of these architectures and explores potential structural issues.

As cloud computing continues to grow, the demand for data centers expands, underscoring the importance of designing an efficient topology. The current wired data center network architecture can be classified primarily into two categories: switch-centered network architecture and server-centered network architecture [14]. Fat-Tree is a representative structure centered on switches. In a Fat-Tree that uses a switch with n ports, there are n pods. Each pod contains $n/2$ switches in both the aggregation layer and the edge layer, while the number of core switches is $n^2/4$. Although Fat-Tree addresses the issue of single points of failure, it presents significant challenges due to its complex wiring requirements.

In the current server-centric network architecture, BCube stands out as one of the typical examples, and its design adopts a recursive approach to scalability. $BCube_0$ is composed of a switch with n ports and n servers, $BCube_1$ is composed of n $BCube_0$ and n n-port switches, $BCube_k$ is composed of n $BCube_{k-1}$ and n^k n n-port switches. Each server has k + 1 ports, a $BCube_k$ has N = n^{k+1} servers, and k + 1 level switches. Facing various bandwidth-intensive applications, BCube offers robust support with multiple parallel paths between different servers, demonstrating excellent fault tolerance. However, BCube requires modifications to the server during scaling, leading to a lack of scalability.

Switch-centric architectures offer limited programmability due to the restricted capabilities of switches compared to servers. On the other hand, server-centric architectures tend to suffer from higher latency. Furthermore, as wired infrastructures continue to expand, the associated wiring complexity and costs also increase, presenting significant challenges. For example, challenges such as low space utilization efficiency, inadequate heat dissipation, hotspot congestion, high power consumption, and intricate maintenance pose significant obstacles. To address these issues, researchers have tried to integrate wireless communication technology into the existing data center network architecture to improve the performance of wired links [15].

The current wireless data center network architecture is divided into two categories: completely wireless data centers (CWDCs) and hybrid data centers (HDCs) [16].

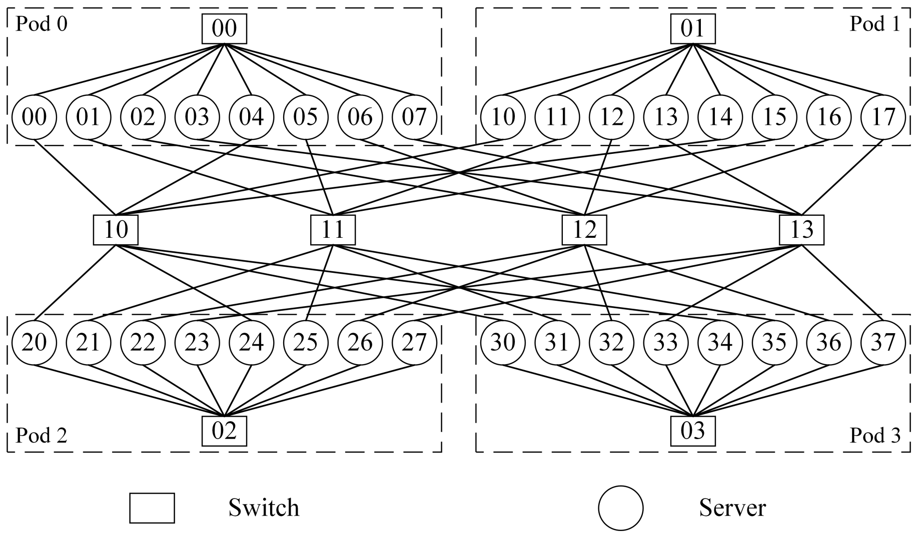


Fig. 1: $RRect$(4, 2, 1) network structure diagram

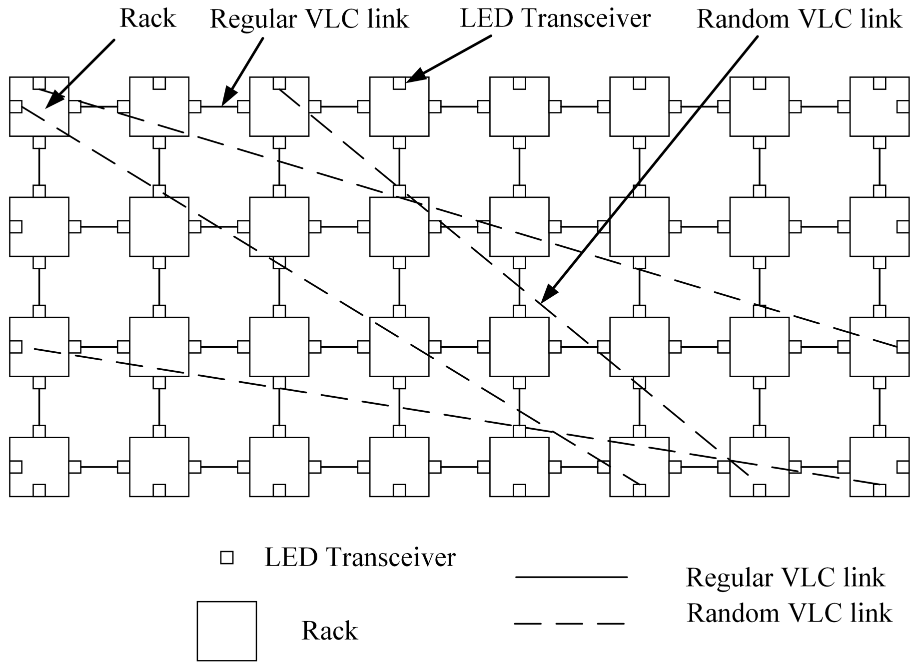


Fig. 2: Wireless hierarchical topology diagram of the rack

CWDCs employ an innovative design that eliminates traditional communication cables, relying on server rack design and strategically placed antennas to create an elegant wireless topology. The researchers designed a server-to-server wireless data center network. The racks in this structure are positioned adjacent to each other in the design. To prevent interference from wireless link signals, wireless links are directly established on the servers [17]. The structure features antennas mounted on the top and sides of the server, facilitating communication paths that transmit signals in both horizontal and vertical directions. Compared to traditional horn antennas, this design minimizes delays caused by mechanical steering, reduces power consumption, and improves throughput. However, it is important to note that, due to the arrangement of the racks, there may be a high number of hops for communication between distant servers.

HDCs fully leverage the underlying infrastructure while incorporating wireless communication technology to integrate wireless links into the network. In hotspot scenarios—such as those involving high traffic volumes that lead to network congestion—the use of wireless links can effectively alleviate congestion and significantly enhance network throughput. This provides substantial optimization for data center network performance. Furthermore, this efficient and flexible solution advances research in the field of data center networking. Shan et al. used the Fat-Tree structure, maintaining the existing wired links and the relative positions of servers unchanged, while incorporating wireless transceiver devices into the current infrastructure. By introducing wireless links, they effectively expanded the capacity of the network . A server or switch on the original wired path can solve hotspot problems through a wireless link. This innovative design seamlessly integrates wireless communication technology while maintaining the same wired in-

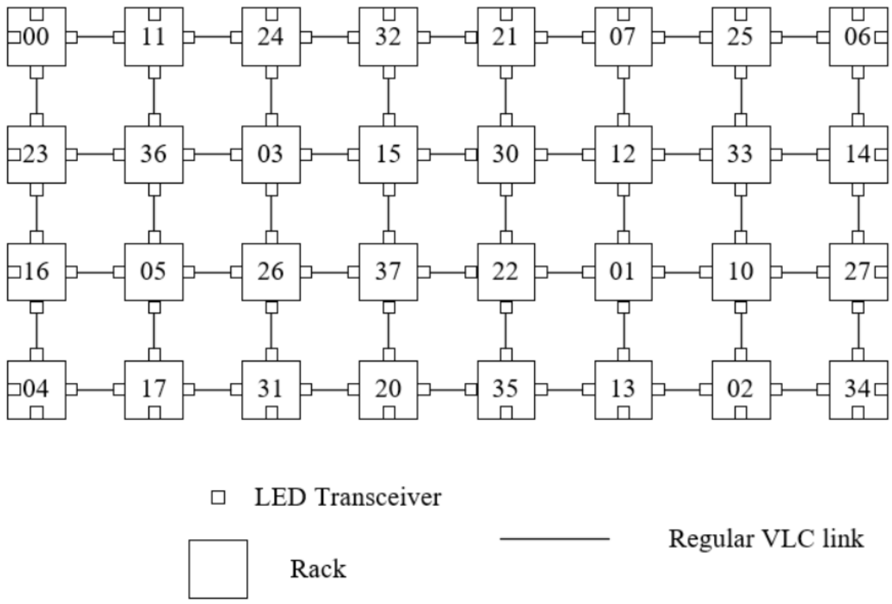


Fig. 3: $VTRNet(4, 2, 1)$ regular link topology

frastructure, providing an effective performance optimization solution for data center networks [18]. In addition to using wireless links to enhance wired connections, Zhang et al. also designed spaces using reflective ceilings to address link blocking and interference issues [19]. However, this method imposes higher requirements on the overall environment of the machine room. Researchers have proposed a structure called graphite, which diverges from the ceiling reflection method for communication. Instead, it leverages its own structural characteristics to address the issue of wireless link blockage and can communicate with multiple nodes of a server within a hop distance [20]. However, once the structure is established, further expansion may require adjusting the location of the transceiver, requiring significant manpower and material resources.

After considering various issues associated with the structure mentioned above, this paper adopts a hybrid approach, combining the wired structure with wireless communication technology to enhance overall performance. We chose a server-centric wired architecture as the foundation and developed a wireless topology at the rack level using visible light communication technology. The hybrid VTRNet structure proposed in this paper can be expanded without altering the original wired structure. This solution enriches routing paths, shortens the average path length, enhances scalability, and reduces the investment of manpower and capital, providing a practical approach to enhance the performance of data center networks.

III. Construction of hybrid data center network

This section introduces the construction process and routing algorithm of VTRNet, a hybrid data center network architecture utilizing visible light communication (VLC) [21]. For the construction process of wireless links, VLC wireless links were added without changing the original wired link connection mode of RRect to construct a hybrid topology. Therefore, it is necessary to describe the process of building the RRect network structure before introducing proposed related methods.

A. Structural characteristics of RRect network

RRect is a server-centric network structure, that is recursively extended and constructed using commodity servers and commodity switches [22].

An $RRect(n, m, 0)$ consists of mn servers connected to a mn-port switch. For $RRect(n, m, k)$, when $k \geq 1$, $RRect(n, m, k)$ is composed of n $RRect(n, m, k-1)$s and n^k mn-port switches. $RRect(n, m, k)$ contains mn^{k+1} servers and (k + 1)n^k switches, of which n^k switches are new switches, and the remaining kn^k switches are in n $RRect(n, m, k-1)$s.

The detailed process of building a network is as follows : The set A is the network $RRect(n, m, k)$ of the A server node, A = $a_k a_{k-1} \cdots a_0, a_i \in \{0, 1, \cdots, n-1\}, i \in \{1, 2, \cdots, k\}, a_0 \in \{0, 1, \cdots, mn-1\}$, when a_i represents the position of $RRect(n, m, i-1)$ in $RRect(n, m, i)$ where the server node is located, a_0 indicates the position of the server node in $RRect(n, m, 0)$, m is a parameter to adjust the size of the network structure, n means $RRect(n, m, 0)$ contains n $RRect(n, m, k-1)$s, k is the level of the network structure. To facilitate routing, the server node encoding A is further converted to $A = a_k a_{k-1} \cdots a_{i+1}\{a_i + \lfloor \frac{a_0}{n} \rfloor \times n\} a_{i-1} \cdots \{a_0 - \lfloor \frac{a_0}{n} \rfloor \times n\}, i \in \{1, 2, \cdots, k\}$. In addition to the server node, the switch S is encoded as $S = s_k s_{k-1} \cdots s_0, s_i \in \{0, 1, \cdots, n-1\}, i \in \{0, 1, \cdots, k-1\}, s_k \in \{0, 1, \cdots, k\}$.Take server node A as an example, the way to connect the new switch is $s_k = k$, $a_{k-1} a_{k-2} \cdots \{a_0 - \lfloor \frac{a_0}{n} \rfloor \times n\} = s_{k-1} s_{k-2} \cdots s_0$. For any server node B that is different from the server node A, encode it in the same way as the server node A. At the same time, the server node B is connected to the switch in the same way to obtain the wired link diagram, $RRect(4, 2, 1)$ is shown in Figure 1.

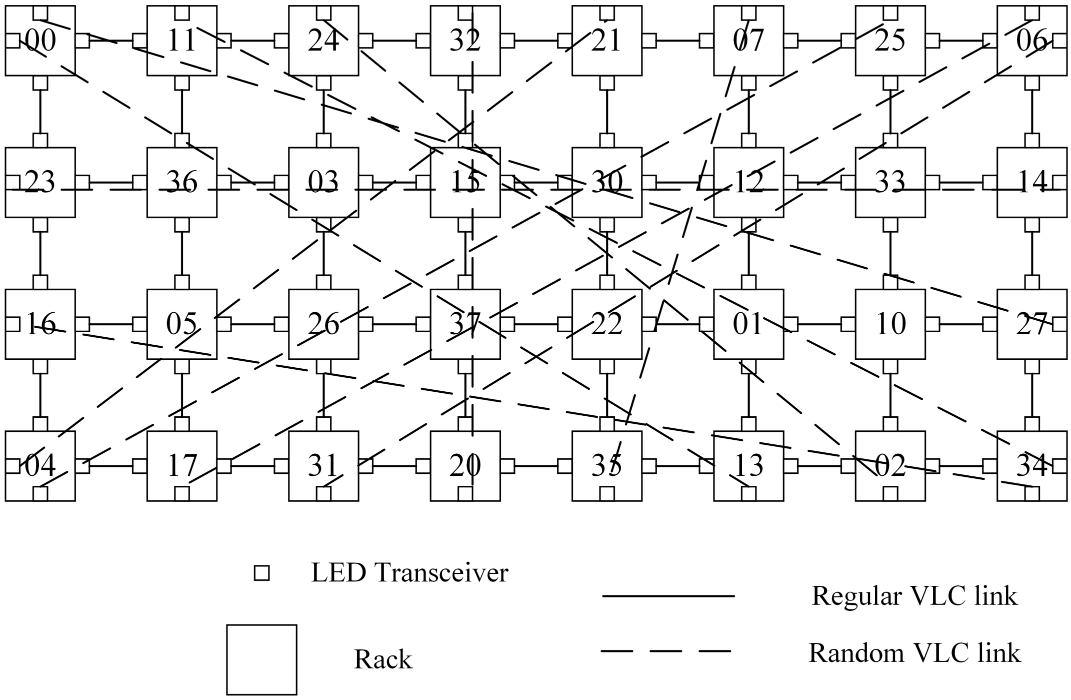


Fig. 4: $VTRNet(4,2,1)$ rack topology

B. VTRNet Network Structure

VTRNet network consists of wired and wireless parts. For the wired part, we organize the server nodes of the RRect structure into racks, with the racks inheriting the coding rules defined for the servers. At this time, multiple servers can be set in the racks, improving scalability. The wireless part is divided into two parts: regular and random. According to the characteristics of wireless small-world network [23], each rack is considered a node in wireless small-world network, and regular links and random links are designed in the grid. To facilitate the subsequent introduction of design rules, we define and introduce the $VTRNet(n,m,k)$ network architecture.

Definition 1 (Basic unit)**.** *VTRNet(n, m, k) contains n VTR-Net(n, m, k - 1)s, and the basic unit represents the secondary structure.*

Definition 2 (Cell node)**.** *The base unit contains multiple racks, and the base unit node is called a cell node.*

In the wire structure of $VTRNet(n,m,k)$, when $n = 4, m = 2, k = 0$, the configuration $VTRNet(4,2,0)$ consists of mn racks, where each basic unit comprises 8 racks. When $k \geq 1$ we take $VTRNet(4,2,1)$ as an example, where $n = 4, m = 2, k = 1, VTRNet(4,2,1)$ contains 4 $VTRNet(4,2,0)$ base units, the number of racks is mn^{k+1}, so there are 32 racks.

The construction of a wireless network follows the characteristics of wireless small world network WSWDC [24]. Each rack is deployed as a node on a two-dimensional grid, while installing 4 LED transceiver devices for each rack, there are 4 regular links on the side of the rack in the grid, the rack at the edge of the grid has a maximum of 3 regular links, and the remaining LED transceiver devices are placed on the top of the rack for the construction of random links. The server nodes in Figure 1 are deployed to their respective locations according to the geometric features in Figure 2.

1) Regular link structures: The method for obtaining regular links is as follows: First, the number of basic units and the number of rack nodes in the wired network structure are determined, and then the rack nodes are arranged on a two-dimensional plane to form a grid structure. The size of the two-dimensional grid is $M \times N$, where M is the number of rows of the two-dimensional grid and N is the number of columns of the two-dimensional grid. The structure formed is similar to a grid structure. The edges of the two-dimensional grid correspond to the designed regular links, and the points on the grid actually correspond to the rack nodes. Each rack node can have up to four regular links connected to its sides. Once the regular links are determined, they correspond to the arrangement of rack nodes in the two-dimensional grid. Therefore, the rack nodes are encoded after the number of rows and columns in the network is determined. The corresponding arrangement rules are determined according to the mode of coding of the rack nodes, and the rack nodes are added to the two-dimensional grid one by one. The arrangement rules for the rack nodes are as follows:

1) For any two different rack nodes, make sure that the two different rack nodes are not in the same basic unit.
2) Based on condition 1, two different rack nodes are connected to two new switches in converted coding mode.

The arrangement rules can be expressed by the following:

$$a_k a_{k-1} \cdots a_1 \neq b_k b_{k-1} \cdots b_1 \tag{1}$$

$$\begin{aligned} & a_{k-1}a_{k-2}\cdots\left\{a_0 - \left\lfloor \frac{a_0}{n} \right\rfloor \times n\right\} \\ & \neq b_{k-1}b_{k-2}\cdots\left\{b_0 - \left\lfloor \frac{b_0}{n} \right\rfloor \times n\right\} \end{aligned} \tag{2}$$

On the basis of meeting Equations(1) and looking for rack nodes meeting Equations(2), rack node A and the rack node

B are placed in adjacent positions of the grid, and then a regular link is constructed.

The rack nodes are placed on a two-dimensional grid according to the arrangement rules, prevents rack nodes in the same base cell and rack nodes belonging to different base cells but connected to the same new switch from being located next to each other in the grid. Adjust the position of the rack nodes several times until all racks are in the proper position. The underlying idea is to place long-distance rack nodes as close together as possible. However, the arrangement of nodes in the two-dimensional grid constructed according to these rules is not unique. The link diagram illustrating these rules is shown in Figure 3.

Rack nodes 24 and 32 need two hops (24-30-32) in the wired link communication mode, and switch nodes are not considered. According to the placement of regular links, rack nodes 24 and 32 are placed in adjacent positions and then connected using regular links to shorten the routing hop count to 1 hop, and the routing path is 24-32.

2) Random link structures: The random link consists of a wireless link formed by a top wireless link transceiver device. According to the characteristics of the small-world network model, the probability of constructing a random link is proportional to the d square of the distance between two nodes of the rack in the wireless structure[23]. d represents the dimension where the node is located. The structure of the wireless link adopts the Grid structure, so the value of d is 2. The random link arrangement rules are as follows:

1) The Euclidean distance calculation method is used to design a preliminary random link.
2) Considering the characteristics of pod connectivity and following Watts and Strogatz's clustering coefficient concept [25], the average clustering coefficient was chosen during the construction of random links. The elements of the structure are regarded as nodes, and a network structure with close relation is constructed at the level of the unit graph, to shorten the average path length.

For any two different rack nodes, calculate the Euclidean distance between the tops of the two rack nodes. First, let the unit of distance between two rack nodes in the two-dimensional grid be 1. In this paper, the Euclidean distance between rack node A and rack node B can be expressed by the following formula:

$$d_{AB} = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \tag{3}$$

where d_{AB} represents the Euclidean distance between the rack node A and the rack node $B, (x_1, y_1), (x_2, y_2)$ are the coordinates of the rack node A and the rack node B in the two-dimensional grid, respectively. In the structure of the wired network, two rack nodes are not connected if the communication distance is only 1 hop. When the wired distance is greater than or equal to 2 hops, the initial random link is constructed, and the selection probability of the random link is proportional to the Euclidean distance.

According to Definitions 1 and 2, base unit VTRNet consists of multiple racks. We also refer to the cells to which the rack belongs as cell nodes. Taking $VTRNet(4, 2, 1)$ in Figure 1 as an example, it contains four basic cells, where racks 00 to 07 belong to one cell, and so on, so there are four cell nodes in total. For any two different rack nodes, if there is an initial random link connection between two rack nodes, the different cell nodes corresponding to the two rack nodes are connected. Under the pod connectivity property, for a cell node corresponding to any rack node in the initial random link, the neighbor nodes connected to the cell node are identified. Then, actual number of edges connected between all neighbor nodes is obtained, and the maximum number of edges between neighbor nodes is obtained. The local clustering coefficient of a cell node is obtained according to the number of actual connected edges between all neighbor nodes corresponding to the cell node and the maximum number of possible edges between neighbor nodes.

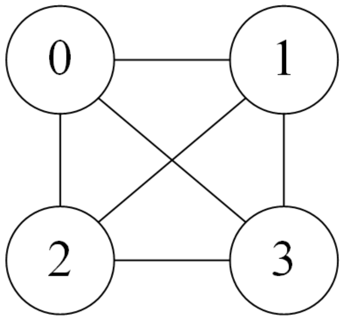


Fig. 5: $VTRNet(4, 2, 1)$ Cell node diagram

For example, for cell node i , cell node i has k_i edges connected to other cell nodes, mark k_i cell nodes connected to cell nodes as neighbor nodes of node i, it can be obtained that k_i neighbor nodes may have at most $k_i(k_i - 1)/2$ edges, the formula to calculate the local clustering coefficient of cell node i can be expressed as:

$$C_i = \frac{2E_i}{k_i(k_i - 1)} \tag{4}$$

where C_i represents the local clustering coefficient of cell node i and k_i represents the number of neighbor nodes connected by cell node i,E_i represents the number of edges actually connected between neighbor nodes connected to cell node i,$k_i(k_i - 1)/2$ represents the maximum number of possible edges between neighbor nodes. For any initial random link, the average value of the local clustering coefficients of the cell nodes is calculated, and the average clustering coefficient of the initial random link is obtained. The formula can be expressed as follows:

$$C = \frac{1}{n} \sum_{i=1}^{n} c_i \tag{5}$$

where C is the average clustering coefficient, C_i represents the local clustering coefficient of cell node i, and n is the number of network nodes. $0 \leq C \leq 1$, when $C = 0$, there is no edge between the neighbors of the node, and when $C = 1$, the network node is fully connected.

Because there are multiple rack nodes in the cell structure, if the rack nodes of two different cells are connected using random links on the random link network layer, the corresponding cell nodes of the rack nodes are connected. It is necessary to calculate the local clustering coefficient C_i of each node in the cell node diagram, and then calculate the average clustering coefficient C according to the local

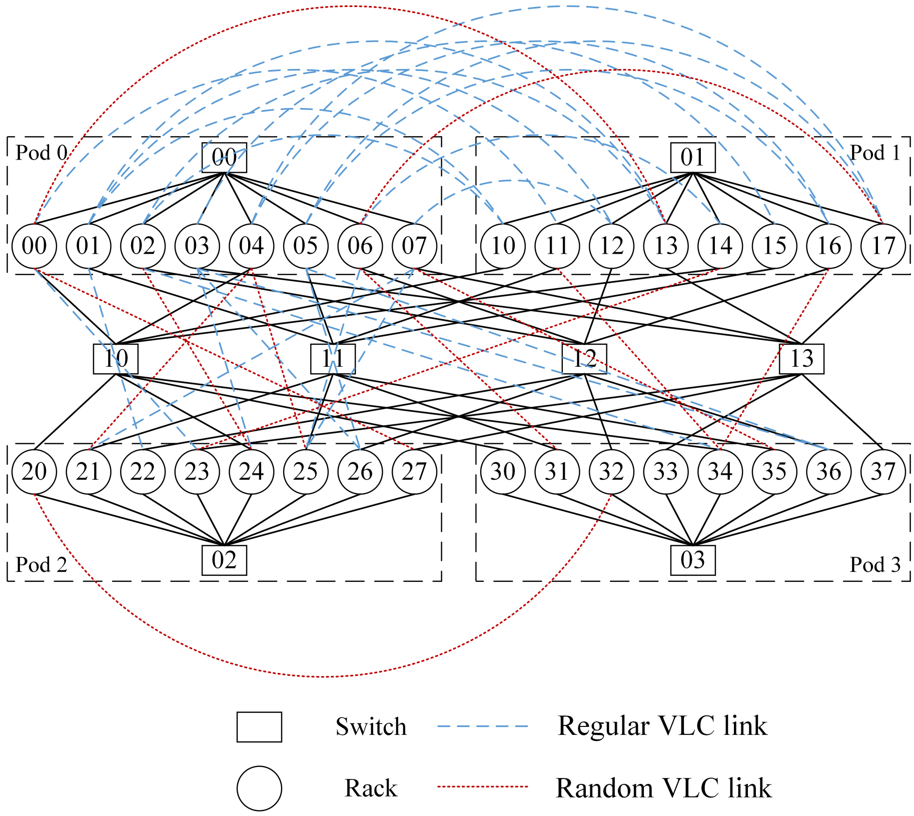


Fig. 6: $VTRNet(4,2,1)$ part of the hybrid structure

clustering coefficient of each cell node. Changing the initial random link several times, the initial random link corresponding to the maximum average clustering coefficient C is determined as the final random link. Figure 4 shows the rack topology.

In Figure 4, rack nodes 00 and 27 are connected by random links between the two racks, so at the level of the cell node diagram, rack node 00 represents cell node 0 and rack node 27 represents cell node 2. Cell nodes 0 and 2 are connected, and 4 cell nodes are connected in this way to form the cell node diagram, as shown in Figure 5.

The average clustering coefficient is calculated only for the cell nodes constructed in the random link network layer and not for other nodes in the regular link network layer. For example, node 2 is substituted in the local clustering coefficient formula to obtain a value of 1, and the local clustering coefficients of all cell nodes are adjusted to obtain the average clustering coefficient value of 1. At this point, the cell node graph exhibits a high clustering property, indicating that the connections between cell structures are tighter, effectively shortening the average path length.

At the same time, due to the limited transmission distance of the LED transceiver and the need to ensure transmission rates, the actual distance for constructing a random link should be less than 10 meters. Optical path interference between random links can be avoided by deploying LED transceivers on top of the rack at different heights in a layered deployment scheme. According to the characteristics of the small-world network and the unit structure of the RRect structure itself, the random link constructed by using European-style distance and clustering coefficient can connect distant rack nodes, and the route hops of some nodes only need 1 hop to complete the communication between two rack nodes, thus shortening the route hops. Figure 6 shows the partial hybrid link structure of $VTRNet(4,2,1)$.

The partial mixed link structure diagram of $VTRNet$ $(4,2,1)$ is formed by adding partial regular links and all random links to the rack in the first basic unit $RRect(4,2,1)$ in $RRect(4,2,0)$.

C. *Routing algorithm*

Since the RRect wired structure is combined with the wireless VLC link, and RRect related wired routing algorithm has been introduced by researchers [22], this section focuses on describing the hybrid routing algorithm.

1) Hybrid routing: The hybrid routing algorithm of VTRNet is designed based on the wired unicast algorithm. A preliminary judgment is made using the conversion mode between codes and Hamming distance. The nodes connected to the source node via the wireless link are considered to form set M, while the nodes connected to the destination node via the wireless link are regarded as set N.

1) Step 1: Determine whether the source node and the destination node are one hop away from each other, if so, output the path directly, otherwise execute step 2.
2) Step 2: Determine whether there is an intersection between sets M and N. If there is an intersection, output the path; otherwise, perform Step 3.
3) Step 3: Update the current node. If the current node meets the conversion conditions, the node will be converted and then the converted node will be used as an intermediate node. Continue to determine the distance between the wired and wireless links in the set N. If the

Algorithm 1 VTRNet hybrid routing algorithm

Input: $src = s_k s_{k-1} \cdots s_0, des = d_k d_{k-1} \cdots d_0, \Pi_k = [\Pi_k, \Pi_{k-1} \cdots, \Pi_0], \Pi$ is a complete permutation of $[k, k-1, \cdots, 1, 0], n$ is a VTRNet parameter that adjusts the network size.
Output: Path from the source node to the destination node.
$src', des' = Convcd(src, des)$; // Converts the encoding of the source node and destination node
$h = CalHD(src', des')$; // Calculate Hamming distance
if $h = 1$ **then**
  $return(src, des)$; // Returns the paths of the source and destination nodes connected to the same switch
else if $Wireless(M \cap N) \neq \emptyset$ **then**
  $return(src, des)$;
else if $Wireless(M \cap N) = \emptyset$ **then**
  for $i = k; i > 0$ **do**
    $tmp\_node = des'[\Pi_i]$;
    $CInter\_node = tmp\_node$; // Find a temporary intermediate node
    if $CInter\_node \geq n$ **then**
      $Inter\_node = TBackc(CInter\_node)$; // Back to encoding
    else if $d_{Inter\_node,des} = 1$ **then**// One hop apart
      $return(src, Inter\_node, des)$;
    else if $Wireless(Q \cap N) \neq \emptyset$ **then** // Q is the intermediate node connected by a wireless link
      $return(src, Inter\_node, des)$;
    else
      $Wireless(Q \cap N) \neq \emptyset$;
      $i - -$;
    end if
  end for
  $path = pathA(src, Inter\_node) + pathB(Inter\_node, des)$;
end if
return path;

distance is one hop, output the path. Otherwise, repeat the process until a complete hop path is found.

IV. Property analysis and experiment

This section analyzes the relevant properties of VTRNet and evaluates the performance of the proposed architecture. The evaluation focuses on link deployment, average path length, cost, and energy consumption, highlighting the advantages of the proposed structure. The experiments were carried out in a Windows 11 (64-bit) environment using MATLAB R2021a. The results demonstrate that VTRNet exhibits excellent scalability, significantly reduces the average path length, and benefits from the flexible expansion of wireless links, thereby enhancing the network's capacity and adaptability.

A. VTRNet property analysis and experiments

Theorem 1. *The degree of a node in a hybrid structure $VTRNet$ is k + 5.*

Proof of Theorem 1. From a rack point of view, the number of ports per rack wired link in hybrid architecture VTRNet

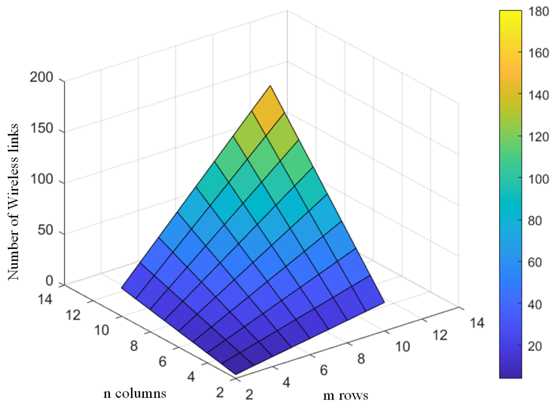


Fig. 7: The number of wireless links contained in the VTRNet in row m column n

is $k + 1$. When adding a wireless link for each rack, four wireless transceiver devices are installed for each rack to form four wireless links, so the degree of each rack node is $k + 5$.

Theorem 2. *The number of links in a hybrid $VTRNet$ is* $(k+3)mn^{k+1}$

Proof of Theorem 2. Since there are $N = mn^{k+1}$ racks in VTRNet, from a rack point of view, each rack has k + 1 wired link ports, so the number of wired links is $(k+1)mn^{k+1}$. There are four wireless transceiver devices in each rack, with a total of $2mn^{k+1}$ wireless links, so the total number of links is $(k+3)mn^{k+1}$.

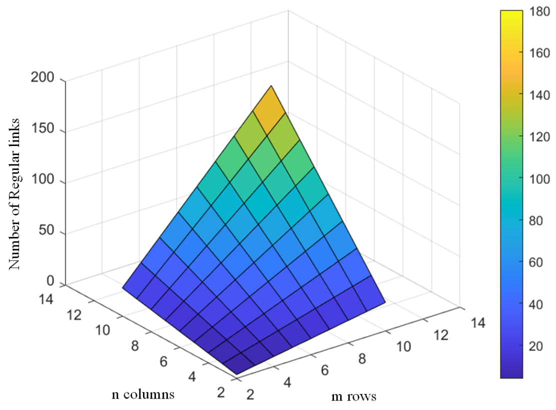
Theorem 3. *In the wireless topology level of $VTRNet$, the ratio between the number of regular links and the number of wireless links is $\frac{(m-1)n+(n-1)m}{(m-1)n+(n-1)m+m+n}$. The ratio of the number of random links to the number of wireless links is $\frac{m+n}{(m-1)n+(n-1)m+m+n}$.*

Proof of Theorem 3. In the wireless topology level of VTRNet, there is a two-dimensional grid structure composed of m rows and n columns, so the number of regular links is $(m-1)n+(n-1)m$. The number of random links is $(m+n)$. Therefore, there are $(m-1)n+(n-1)m+m+n$ wireless links, from which the proportion of regular links and random links in the total of wireless links can be calculated.

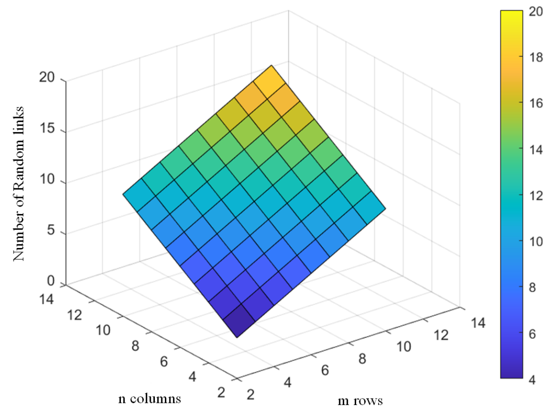
Figure 7 shows the number of wireless links that change with m rows and n columns. Figures 8a and Figure 8b show the evolution of the number of regular links and random links, respectively, regarding m rows and n columns. Furthermore, Figures 9a and Figure 9b display the respective proportions of regular and random links in the total count of wireless links. respectively.

It can be seen in Figure 7 that the total number of wireless links is 200 under the condition of 10 rows and 10 columns. As shown in Figures 8a and 8b, with increasing rows of m and columns n, the number of regular links and random links gradually increases, and the number of regular links accounts for the majority. When the number reaches 10 rows and 10 columns, the number of regular links is 180 and the number of random links is 20.

As shown in Figures 9a and Figure 9b, as the number of

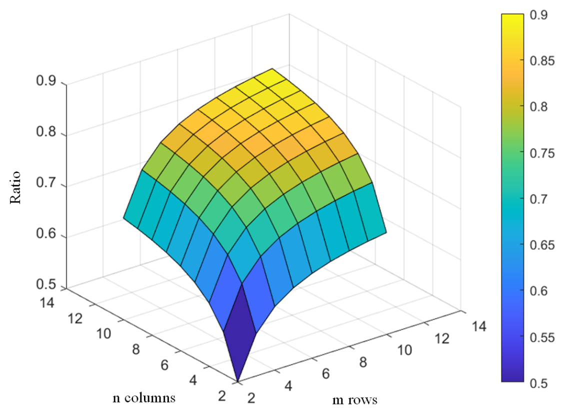


(a) The number of regular links in the VTRNet with m rows and n columns

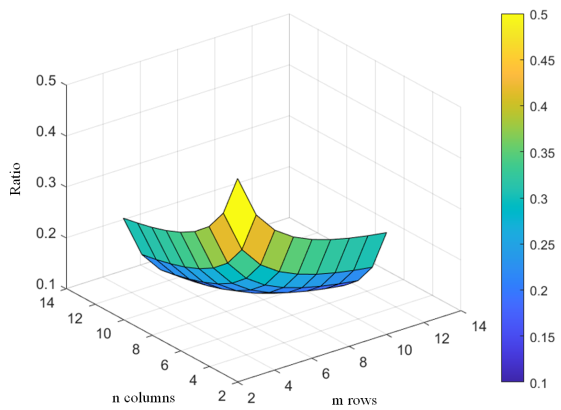


(b) The number of random links in the VTRNet with m rows and n columns

Fig. 8: The variation in the number of wireless links with m rows and n columns



(a) The proportion of VTRNet regular links in m rows and n columns



(b) The proportion of VTRNet random links in m rows and n columns

Fig. 9: The proportion of wireless links with m rows and n columns

rows and columns increases, the proportion of regular links in the total number of wireless links gradually increases, while the proportion of random links decreases. Random links serve as links between connecting cell nodes and are therefore in the minority, which is in line with the expectations of the structural design. At the same time, regular links are used to connect distant rack nodes. The two types of wireless link enrich the routing path and shorten the communication distance between nodes.

Figure 10 shows that when the number of ports on the switch is set to 24, the number of nodes can be varied by adjusting the values of m and n. When the parameters $m = 2$ and $n = 12$, the number of rack nodes changes the fastest. It should be noted that even if the number of switch ports is the same, changing the values of the parameters m and n can also result in a different number of rack nodes. Therefore, the structure can adjust the required number of rack nodes at any time according to demand, reflecting the flexibility of the structure. Figure 11 shows how the number of wired links varies with the parameters m and n when the number of layers is fixed at layer 1. Although the current configuration consists of a single layer, the number of wired links increases rapidly as the parameters m and n grow. Meanwhile, the number of racks in the architecture can be adjusted according to the parameter m, allowing flexible scaling of both rack and link quantities according to the actual requirements of the data center.

B. *Topological performance analysis*

As shown in Figure 12, the average path length of VTRNet is shorter than that of RRect. In RRect, four LED-based wireless transceivers are added to each rack, forming wireless links that can connect distant rack nodes, thus shortening communication distances. However, this advantage diminishes as the number of network layers increases. This is because the proportion of wireless links relative to wired links decreases with additional layers, reducing the performance gain provided by wireless communication. As a result, VTRNet exhibits diminishing marginal returns, and the reduction in average path length becomes less significant.

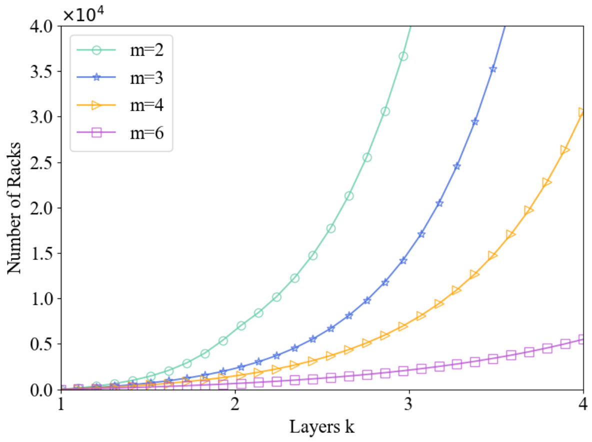


Fig. 10: Number of rack nodes corresponding to different parameters m and number of layers k

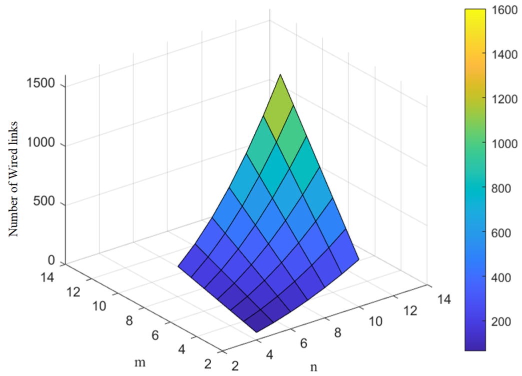


Fig. 11: Number of wired links corresponding to different parameters m and n

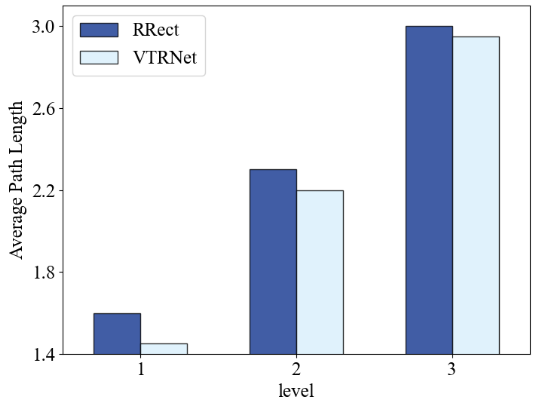


Fig. 12: Average path length comparison

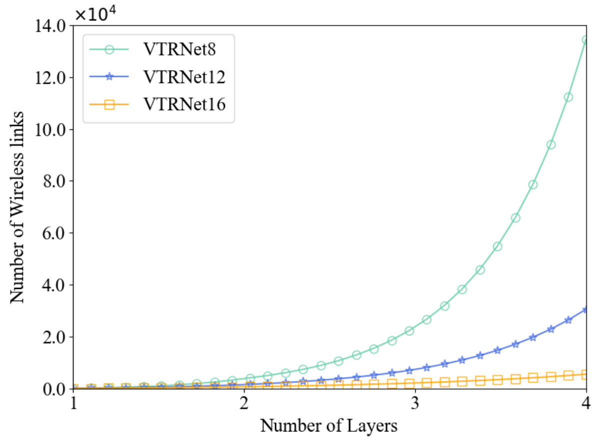


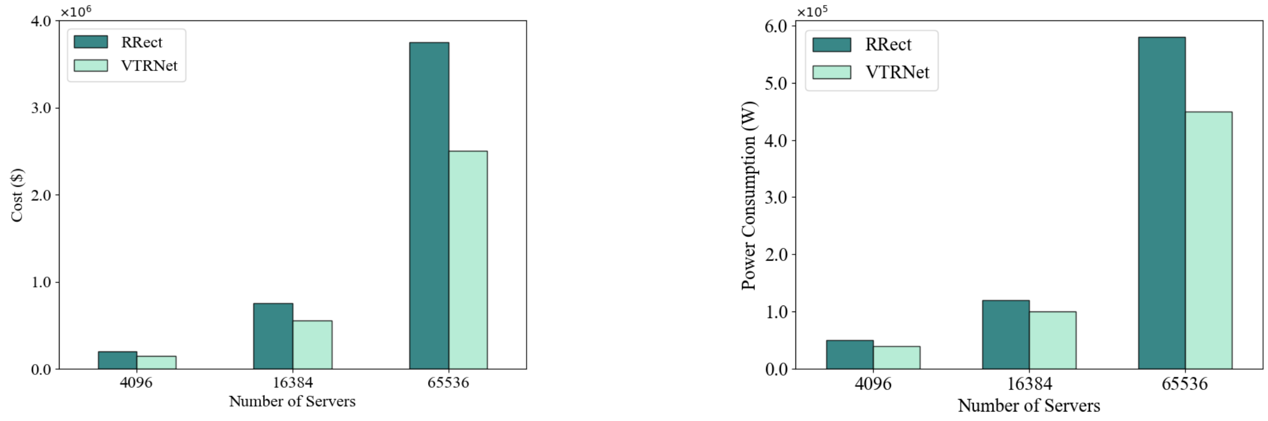
Fig. 13: The number of wireless links under different number of ports and level K

Therefore, the advantages of VTRNet are more pronounced in small-scale data centers.

In the VTRNet structure, m rows and n columns are used to construct a two-dimensional grid structure. In Theorem 3, the changes in the number of wireless links and the number of columns have been analyzed. Because each rack has four fixed wireless transceiver devices and VTRNet adds wireless links based on RRect, the number of wireless links $N = 2mn^{k+1}$. Therefore, this section will analyze the changes in the number of wireless links under different port numbers and different network levels. As shown in Figure 13, when $n = 6$ and $m = 2$ in $VTRNet$, the number of ports on the switch is 12, and the network level is $k = 2$, there are 864 wireless links, and the number of occupied lines is nearly 66.7%. It can be seen that with the expansion of the network level, the number of wireless links gradually expands. At the same time, when the parameter of the network structure $m = 2$ is constant, the larger n is, the greater the number of ports mn of the switch and the more wireless links are added. Therefore, VTRNet uses the LED wireless transceiver device to improve scalability.

The added wireless links enrich the communication path of the original line structure, and are more balanced in the communication load, avoiding hotspot congestion. There are more links between nodes and the communication modes are diversified, which reduces the possibility of communication efficiency reduction caused by link failures. VTRNet can flexibly change the number of wireless links to meet different needs by selecting different switch ports and network layers.

Cost and energy consumption are two critical factors in the construction of data centers. To comprehensively evaluate these metrics, this study analyzes the cost and energy consumption of the VTRNet and RRect architectures under three different server configurations: 4,096, 16,384, and 65,536 servers. The selected switch model for the experiments is the T1600G-28T, and LED light-emitting diodes are used as wireless transceiver devices. Since comparisons are conducted on the same network scale with equal numbers of servers, the cost and energy consumption of the servers themselves are excluded from the analysis. Figure 14 illustrates the comparison of cost and energy consumption between the two architectures. As shown, when the number of servers is 4,096, the cost and energy consumption of the two architectures are very similar. However, as the scale increases, the advantages of VTRNet become more apparent. When the number of servers reaches 65,536, the cost of RRect is approximately 1.49 times that of VTRNet, and its energy consumption is about 1.31 times higher. Therefore, VTRNet demonstrates greater advantages in building low-cost and energy-efficient data center networks.



(a) Cost and expenditure comparison

(b) Power consumption comparison

Fig. 14: A comparison diagram of cost and energy consumption

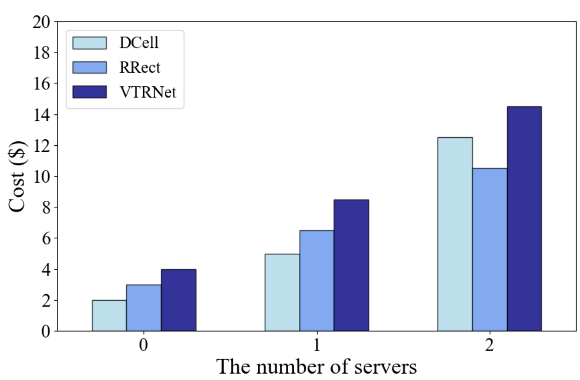


Fig. 15: Network throughput at different scales

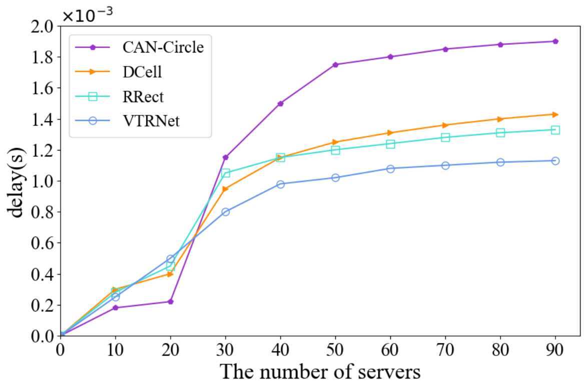


Fig. 16: Delay comparison graphs of different network structures

C. Network Performance Analysis

To evaluate the performance of network architecture throughput, this study transmits data packets at a fixed rate and measures the total amount of data successfully delivered by each architecture. Figure 15 presents a comparison of the performance of VTRNet, RRect, and DCell on different network scales. The results show that in small-scale networks, the throughput of VTRNet is approximately twice that of DCell. As network scale increases, VTRNet consistently outperforms both RRect and DCell in terms of throughput, demonstrating its significant advantage in handling high-bandwidth demands, which makes it well suited for modern data center applications.

This study compares the latency performance of the VTRNet architecture with that of the RRect and DCell architectures. As shown in Figure 16, when the network scale is small, the latency differences between the architectures are minimal, with VTRNet exhibiting slightly lower latency than RRect and DCell. As the complexity of the network increases and the number of servers exceeds 20, overall latency rises rapidly. Compared to other architectures, VTRNet, by using hybrid links for routing, shows a more gradual increase in latency as the network scale expands. Additionally, its overall latency remains lower than that of the CAN-Circle, RRect, and DCell architectures. This result is consistent with the earlier analysis of wireless link performance, indicating that VTRNet provides overall superior low-latency characteristics.

V. Conclusion

In summary, VTRNet introduces a wireless structure at the rack level and incorporates corresponding wireless links while maintaining the original $RRect(n, m, k)$ wired architecture. It enables flexible deployment and easy expansion without altering the existing structure. As the wired topology scales, the path length between racks connected by wired links gradually increases. The hybrid structure addresses this by integrating wireless links alongside the wired connections.

Racks are positioned on a two-dimensional grid, with adjacent racks connected by regular (wired) links. The design of random links considers the probability of distant connections in a small-world network, as well as the average clustering coefficient, to optimize link placement. This approach enables flexible wireless link deployment, facilitates scalability, reduces maintenance costs, resolves complex wiring challenges, shortens the average path length, and enhances the overall performance of the RRect network.

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