Zhang et al. Journal of Cloud Computing (2023) 12:165
https://doi.org/10.1186/s13677-023-00545-0

Journal of Cloud Computing:
Advances, Systems and Applications

RESEARCH **Open Access**

Design and analysis of wireless data center network topology HCDCN based on VLC

Qingfang Zhang[1], Xiaoyu Du[1*], Jie Li[2] and Zhijie Han[3]

Abstract

With the rapid development of the Internet of Things, big data, cloud computing and other industries, the data center network, as the core infrastructure of the computing industry, is becoming increasingly important. Wireless communication technology is developing rapidly. This paper uses visible light wireless communication technology to build a wireless data center network, solving the problems of complex wiring and expansion difficulties in the existing data center network.

Aiming at the problems of insufficient spectrum, low bandwidth utilization and large energy consumption in the existing wireless data center, this paper adopts the visible light wireless communication technology based on LED, and proposes a new wireless data center network structure HCDCN. Firstly, work have been done to analyze the feasibility of introducing data centers in this technology, and transform server racks in combination with the characteristics of the technology. Secondly, the construction process of the structure is introduced and a new coding rule is proposed. In order to increase the routing efficiency and fault tolerance, the rack top link routing path is added, and an efficient routing algorithm is designed. Finally, the aggregate throughput of HCDCN under different scales is obtained through experiments, and the network performance of HCDCN structure is compared with that of OWCells and Mesh structure. Experiments have proved that HCDCN's network performance is better than the other two structures under the same conditions. The new wireless data center network proposed in this paper has largely alleviated the bandwidth shortage of hotspot servers.

Keywords Wireless data center network, Visible light communication, HCDCN, Structure design, Routing algorithm

Introduction

The 21st century is an era of great development of data and information. Mobile Internet, social network, e-commerce, etc. have greatly expanded the boundaries and application scope of the Internet, and various data are rapidly expanding and expanding [1]. The number of Internet applications based on cloud computing and the Internet of Things are also increasing rapidly, constantly putting new demands on data centers. As the foundation of cloud computing [2], data centers can provide powerful parallel computing and distributed storage capabilities to manage, operate and analyze massive data, and have become an indispensable infrastructure for economic and social operation, playing a crucial role in the development of the digital economy. Data center network [3] is a network for connecting massive computing and storage nodes. Its application fields have covered all aspects of information development, such as life, military, and finance, so the requirements for data centers are also increasing.

The traditional wired data center network topology is mostly based on tree design, and usually adopts three-layer structure, such as Fat-Tree [4], VL2 [5], etc. With

*Correspondence:
Xiaoyu Du
dxy@henu.edu.cn
[1] School of Computer and Information Engineering, Henan University, Kaifeng 475004, China
[2] School of Intelligent Engineering, Zhengzhou University of Aeronautics, Zhengzhou 450046, China
[3] School of Software, Henan University, Kaifeng 475004, China

the increasing demand for the data center network scale, the tree-type structure has a higher demand for the upper layer switches, which brings high deployment costs and complex cabling process when expanding. Subsequently, researchers proposed a new wired data center network structure based on recursive topology such as DCell [6], FiConn [7] and BCube [8]. Although it improves the scalability and fault-tolerance of the network, it still does not meet the current transmission requirements of high bandwidth and low latency. The scale of the data center is huge [9], staff need to spend a lot of time, money, and energy in the process of designing, deploying, and maintaining cables and optical fibers. Moreover, the close arrangement of server racks will cause the problems of heat dissipation, which will make the management and maintenance of servers in the data center more difficult.

In view of these problems in wired data centers, some researchers have proposed wireless data center solutions. Static wireless data center structure has a wide range of applications in modern society. With the rapid development of information technology, the growth of data volume and the demand for data processing are also increasing. Static wireless data center structure can also be used in fields such as cloud computing, big data analysis, and artificial intelligence. These fields require a large amount of data processing and storage, and static wireless data center structure can provide efficient, reliable, and secure data processing and storage services, thus meeting the needs of modern society for data processing and storage. Wireless data center network has many advantages, such as high flexibility and simple installation. Wireless communication technology has no complex wiring problems, and minimizes the cost of money and manual maintenance [10]. At present, wireless communication technology mainly includes 60GHz millimeter wave, free space light and visible light wireless communication technology [11, 12]. Many researchers have proposed to alleviate congestion by adding wireless communication technology to the large data center network [13–17], but these solutions have some disadvantages, such as over-dependence on the ceiling, the need for accurate alignment of signal receiving devices, and poor penetration ability. These shortcomings will affect the development of wireless data centers.

Aiming at the problems of existing millimeter wave and space laser wireless technology wireless data centers such as difficult expansion, insufficient spectrum, low bandwidth utilization, harm to human health, and high energy consumption, this paper proposes a wireless data center network topology based on LED visible light wireless communication technology [18–20], which uses VLC links to build a complete wireless data center network structure at the rack level. The proposal of this structure is of great significance for the large-scale development of data centers, and provides ideas for the subsequent design of data center network architecture and routing. Its contributions are as follows:

- ♦ Combined with the characteristics of low power consumption, long life and large bandwidth of VLC, the server rack is transformed into a regular hexahedron, making it more suitable for the data center network structure of visible light communication. The design and proposal of the rack solves the problem of mutual interference between optical paths and provides new ideas for the design of wireless data centers.
- ♦ The construction method and coding rules of HCDCN topology are given. According to this method to build the data center, the rack can be expanded according to a honeycomb structure, which not only ensures signal transmission quality and heat radiation requirements, but also effectively reduces network diameter. The novel wireless data center network topology HCDCN proposed in this paper provided a new method for data center structural design.
- ♦ According to the characteristics of HCDCN structure, the HRA routing algorithm is designed. The algorithm can calculate the most suitable data transmission path in advance, effectively reduce the congestion and delay in the data transmission process, and improve the connectivity of the data center network structure. The design of HCDCN structure provided ideas for the design of data center network routing.

This paper is set as follows. Chapter 2 discusses the existing technology and application. Chapter 3 proposes the construction rules and routing design of HCDCN. Chapter 4 analyzes the properties of HCDCN structure, and then carries out experimental simulation to evaluate its performance. Chapter 5 draws a conclusion.

Related work

With the development of wireless communication technology, more and more researchers have constructed data centers based on wireless technology. At present, the most common wireless communication technologies include millimeter wave communication technology, visible light communication technology, and so on. However, these data centers have some problems in terms of structural expansion and data transmission efficiency. The advantages and disadvantages of these structures will be described below.

In [13], Shihada et al. proposed a wireless data center network structure based on 60GHz millimeter wave technology. In the paper, the server is arranged in a cylindrical rack, which is convenient to establish communication channels between racks and form a dense connected grid. Each server's network card is replaced with Y-Switch, and the data exchange structure is aggregated to the server node so as to achieve the purpose of tight connection between server nodes and supporting fault recovery. This structure realizes wireless full connection, greatly reducing the complexity of wiring, and saving labor and money. However, the 60GHz millimeter wave wireless signal will decay rapidly with the increase of transmission distance. The extremely small obstacles encountered in the transmission process will also affect the signal transmission, resulting in network instability, high equipment cost and low security.

Qin [21] et al. proposed a novel VLC enabled Wireless Small-World Data Center (WSWDC). It employs VLC links to achieve a fully wireless connectivity between racks for the first time, and thus reducing hardware investment, as well as maintenance cost. They first use regular VLC links to interconnect racks as a regular grid data center network and optimize the rack placement to shorten the average path length and the network diameter. To further exploit the benefits of VLC links, a few random VLC links are introduced to update the wireless grid data center network as a wireless small-world data center network. Although it is beneficial to introduce wireless transmission into data center network, there are still many problems, including media access control coordination of directional transmission, multi-path routing, etc. These topics need to be further studied to improve the feasibility and efficiency of wireless data center network.

In [22], Cao et al. proposed wireless data center network as one of the next generation network technologies for data centers, which has important research significance. Through image processing, they established a radio propagation model based on a heat map. By considering objectives of coverage, propagation intensity and interference intensity as well as the constraint of connectivity, they formulated the topology optimization problem as a multi-objective optimization problem. However, this paper mainly focuses on how to reduce interference between wireless beams while neglecting how to improve wireless connectivity, which may lead to a decrease in overall performance of a wireless data center network structure.

In [23], Chen et al. proposed a wireless data center network structure called Graphite. The Graphite 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. This structure ensures the smoothness of wireless communication links within the structure by increasing the connectivity and average point degree between racks. 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 you want to expand the Graphite structure, you need to reconfigure the height and direction of all antennas in the structure. The process of redeployment requires a significant amount of manpower and financial re-sources, and can also lead to a decrease in the flexibility of the entire network.

The above structures are all designed based on wireless communication technology. The wireless transmitter is placed on the top of the rack to build wireless data transmission links to increase network connectivity and ensure smooth operation of the data center network. However, these structures do not consider the issue of expansion. When the network topology is completed, if you want to expand, the entire network needs to be rebuilt, which consumes a lot of manpower and money, and will greatly reduce the flexibility of the entire network. Wireless data center network topology HCDCN proposed in this paper fully considers these issues and combines the characteristics of visible light wireless communication technology to transform the rack. This structure can expand the network topology according to requirements without changing the existing structural foundation, which greatly reduces the investment of manpower and money. The new wireless data center network proposed in this paper has largely alleviated the bandwidth shortage of hot servers in large traffic data centers.

Construction rules and routing design of HCDCN

This chapter shows a wireless data center network topology based on LED visible light communication. Combined with the technical characteristics to transform the server rack, the physical model construction process of HCDCN is represented. In order to realize the interconnection of all racks, new coding rules are defined in this chapter.

Physical model

In the construction process, HCDCN is designed as a static wireless structure. It is not necessary to adjust the transceiver and link with the help of complex centralized control mechanism to achieve the purpose of plug and play.

In order to make visible light communication more suitable for introducing into the data center network structure, the traditional server rack needs to be transformed. Firstly, by installing LED communication transceiver on the side of each server rack, and then increasing the number of ports in the server rack to improve the routing efficiency by increasing the number of wireless links. In HCDCN, the optical path cannot be changed, so if you want to establish an anti-jamming communication path between the server racks, you need to make sure that the transceivers of the destination rack and the source rack can fully match each other.

VLCcube [24] is the first data center network using VLC link. In VLCcube, the traditional cube server rack is used. As shown in Fig. 1(a), the entry and exit degrees of each node are 4. With the increase of the number of faces, the degree of nodes will also increase, which is convenient to improve the routing efficiency. However, in practical applications, only regular hexahedron is most suitable for VLC communication, as shown below.

The biggest disadvantage of VLC communication is the mutual interference between optical paths, followed by the impact of the distance between transceivers on the data transmission rate. As the red links in the regular octahedron interfere with each other due to their crossing, they would become invalid links. Therefore, the number of adjacent nodes that can be communicated by each node in the regular octahedron is 4, and the entry and exit degrees of nodes are also 4. The maximum transmission rate that a single LED can provide is related to the distance. At a distance within 1m, a single module of VLC wireless link can transmit at a speed of more than $20Mb/s$ in a short distance. Therefore, under the condition that the optical paths do not interfere with each other and the LED transmission efficiency could be guaranteed, the regular hexahedron is the most suitable for VLC link deployment. When the regular hexagonal server rack cluster is deployed, the distance between the racks should be minimized to achieve maximum transmission efficiency.

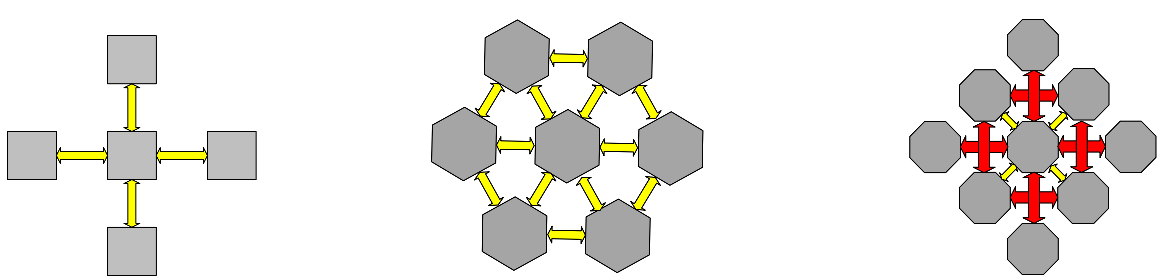
Topology construction and coding rules

The HCDCN structure is gradually expanded from a regular hexahedron. The first layer is a regular hexahedron, which could be expanded once to seven regular hexahedrons. The six regular hexahedrons in the second layer have one side corresponding to one side of the first regular hexahedron. By extending in this way, the racks can be connected to form a similar honeycomb structure. Each rack is called $HCDCN_0$ as a structural unit of HCDCN, and $HCDCN_0$ is used as a basic block for layer-by-layer expansion. Each port of $HCDCN_0$ rack is numbered clockwise, and a rack is placed every 60° of rotation. The port number of the corresponding rack is fixed, which is 1 and 4, 2 and 5, 3 and 6 corresponding to each other.

The structure is represented by HCDCN(n,m), where n represents the number of expanded layers and m represents the number of $HCDCN_0$ added at the outermost layer. And the number of server racks could be calculated according to the formula "$S=3n(n+1)+1+m$". When the number of outermost $HCDCN_0$ is $6n$, it means that the outermost rack is full, the number of server racks is $S=3(n^2+n)+1$. $HCDCN_1$ is composed of 7 $HCDCN_0$. When layers are full, $HCDCN_n$ is composed of $3(n^2+n)+1$ $HCDCN_0$. Figure 2 is a schematic diagram of the structure when the number of extended layers is 0,1 and 2 respectively.

Each rack of the HCDCN structure is regarded as a node with 6 ports, which is connected with the other 6 adjacent nodes through LED wireless links to form a complete network diagram. It can be seen from Fig. 2 that HCDCN has hierarchy and self-similarity. In order to facilitate counting, new nodes are added clockwise from the first port on the upper left.

The node coding is represented by the address array $q_nq_{n-1}...q_1q_0$, where n is the number of extended layers, at this time, $q_n=n$, $q_nq_{n-1}...q_1q_0$ is expanded by $q_{n-1}...q_1$, that is, the rack directly connected to $q_{n-1}...q_1$. And q_0



(a)Regular tetrahedron rack (b)Regular hexahedron rack (c)Regular octahedron rack

Fig. 1 VLC link diagram for regular tetrahedron, regular hexahedron, and regular octahedron racks

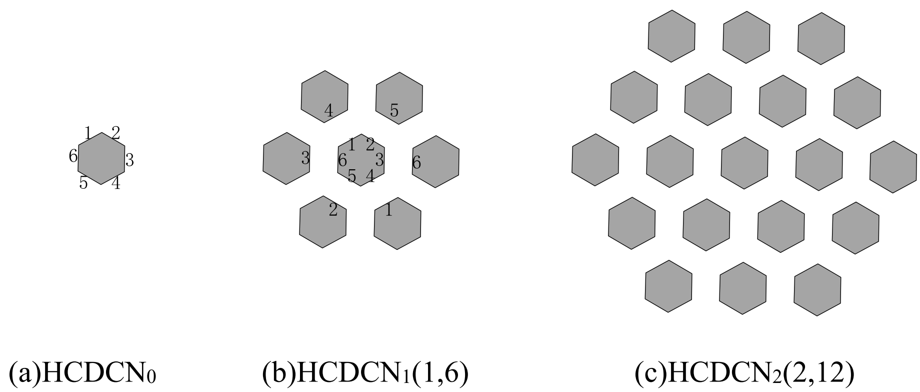


Fig. 2 It's a schematic diagram of the structure when the number of extended layers is 0,1 and 2 respectively

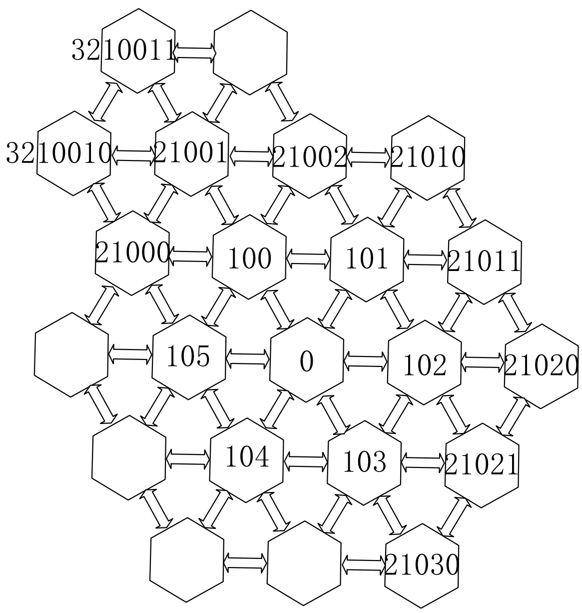


Fig. 3 HCDCN$_3$(3,3) topological structure diagram and partial coding

represents the number of the clockwise count of the upper rack directly connected to $q_{n\text{-}1}...q_1$.

Figure 3 shows HCDCN$_3$(3,3) topology and some node codes. It can be seen that the node code of the higher layer is determined by the node code of the lower layer which is directly connected with it. For example, the rack 3,210,011 is extended from the rack 21,001. The first significant digit represents the number of layers to which it belongs, and the last digit show that it's the first expanded rack of the rack 21,001. This can determined the logical location of each node and the rack code directly connected to it.

Wireless link construction and optimization

In order to improve the connectivity of HCDCN network, reduce the network diameter and increase the routing efficiency, two kinds of wireless links of HCDCN network are designed: regular link and rack top link. Regular link refers to the link established between LED transceivers installed on the side of the rack, as shown in Fig. 4(a). Rack top link refers to the

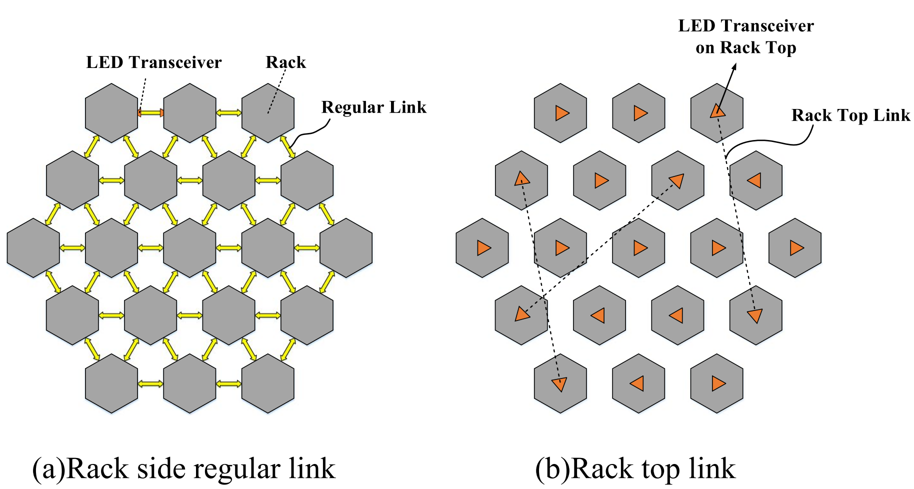


Fig. 4 Two link diagrams of VLC, which are rack side regular link and rack top link

link established by installing LED wireless transceiver on the top of the rack, as shown in Fig. 4(b). The transceivers of regular links are installed at the same location on each side of the rack, the non-intersecting paired rack top links are installed at the same layer, and the cross-linked rack top links are installed at different layers to avoid link interference. The rack top link placement method is described in detail below.

In the VLC wireless communication link, there are two adverse factors: (1) If the LED optical path is blocked, it will not be able to communicate; (2) The transmission rate will decrease with the increase of communication distance. In order to minimize the impact of these two factors, the rack should be expanded fully in accordance with the circular honeycomb structure. In order to ensure the signal transmission quality and meet requirements of the heat dissipation, the distance between adjacent racks should be set as $1m$.

The rack top link directly connects some node pairs that are separated by multiple hops, in order to route more effectively, some rules and conditions are introduced when constructing the rack top link. First, each rack node can be represented by a coordinate in the Cartesian coordinate system. Each rack is assigned an identifier, and the racks in row i and column j in HCDCN are represented as r_{ij}. As shown in Fig. 5, a rectangular coordinate system is established, and the rack corresponds to one coordinate in turn, which also paves the way for the design of the following routing algorithms.

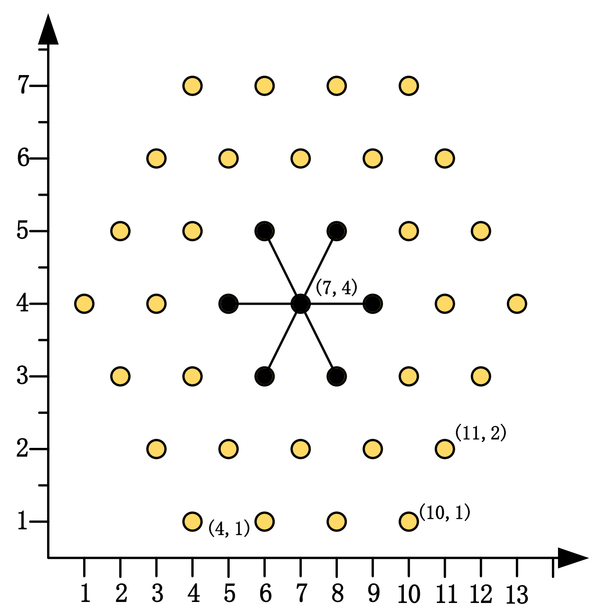


Fig. 5 Two-dimensional HCDCN in plane coordinate system

The transceiver of rack top link is installed on the top of the rack, and Fig. 4(b) is the top view of the rack top link. The rack top link, as a communication shortcut between two racks with relatively long distance, greatly reduces the network delay and network diameter, and increases the degree of nodes. In actual deployment, in order to reduce the interference between optical paths and control costs, only one additional LED transceiver is introduced above each rack, making the degree of each rack increase by 1. For a network with a rack size of M, the total number of rack top links is $M/2$.

Installing rack top links according to certain rules could shorten the average path length and improving routing efficiency. The construction of rack top links is completely random in theory. However, we introduce certain rules to make it applicable to honeycomb wireless data centers based on visible light communication. Taking $HCDCN_2(2,12)$ as an example, it is illustrated in combination with Fig. 6.

The first criterion for rack top link design is: set the length of all regular links as 1, and then introduce the Manhattan distance applicable to this structure:

$$d_M(x,y) = |y_i - y_j| + \frac{1}{2}\left|(x_i - |y_i - y_j| - x_j) - x_j\right| \tag{1}$$

In the coordinate system, (x_i,y_i) and (x_j,y_j) are used to represent the positions of two racks, and each rack pair in the network structure is assigned a value proportional to the square of $d_M(x,y)$ according to the formula. This value is normalized to interval (0,1), which can represent the probability of two racks establishing wireless links. Based on this probability, the rack top link with efficient routing can be constructed.

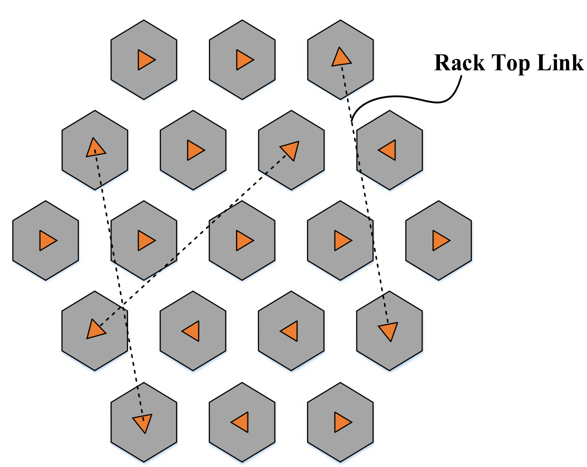


Fig. 6 Wireless rack top link diagram of $HCDCN_2(2,12)$

Theorem 3.1 $d_M(x,y)$ is the Manhattan distance between (x_i,y_i) and (x_j,y_j). The larger $d_M(x,y)$ is, the more efficient routing is for establishing random links between these two nodes.

Proof The Manhattan distance $d_M(x,y)$ in this structure is the shortest distance transmitted between two nodes through regular links. The larger the $d_M(x,y)$ is, the longer the communication delay between the two nodes. Therefore, the larger x and y of the $d_M(x,y)$ is, the better the improvement of the network performance will be by establishing the rack top link between the two nodes. Here is an example.

For example, in Fig. 5, the Manhattan distance between (4,7) and (4,5) is $|5–7|+\frac{1}{2}|7–2\text{-}5|=2$, and that between (4,7) and (5,4) is $|4–7|+\frac{1}{2}|7–3\text{-}5|=3$. Therefore, the probability of establishing wireless links between racks (4,7) and (5,4) is higher.

The improved Manhattan distance between two arbitrary nodes is the number of hops for communication through regular links. Therefore, the larger Manhattan distance means that, establishing rack top link between the two nodes will greatly shorten the routing time and network delay.

The second criterion for rack top link design is: The links should be designed in the same direction as far as possible to avoid blocking and interference between optical paths. The rack top link usually spans multiple racks to establish the link, which will cause the optical path to block or cross. Because the light source based on LED visible light communication cannot concentrate energy as the laser, its directivity cannot be guaranteed to transmit in a strictly straight line, and the optical path will gradually widen. Furthermore, the LED transceiver has high sensitivity, which cannot distinguish interference signal from the source signal. Therefore, the rack top link transceiver should be installed in the same direction as far as possible, and adjusted to different heights in case of optical path crossing. Figure 6 shows the wireless rack top link diagram of $HCDCN_2(2,12)$.

The distance limit of VLC transmitter should be considered when the rack top link is actually deployed. If the distance between the two racks is farther, the probability of establishing rack top link for communication is greater. These rack top links can reduce the path length of network routing and shorten the network diameter. However, the transmission distance based on LED visible light communication is limited. Within $10m$, VLC links can communicate at a transmission rate of $10Gbps$, and the transmission rate beyond this distance will be greatly reduced.

Therefore, the length of the rack top link should be limited. In order to ensure that the length of rack top link cannot exceed $10m$, the Euclidean distance between rack pairs should be calculated first. For the rack pair with Euclidean distance greater than $10m$, its Manhattan distance will not be calculated, and directly set its probability value to 0. If the Euclidean distance between two adjacent racks is L, a pair of racks (x_i,y_i) and (x_j,y_j) connected through the rack top link must follow the following formula:

$$\frac{10}{L} \geq \sqrt{\left|x_i - x_j\right|^2 + \left(\frac{\sqrt{3}}{2}\left|y_i - y_j\right|\right)^2} \tag{2}$$

Routing algorithm design

Routing strategy is one of the important parts of designing the network structure. It is necessary to consider the construction of the optimal transmission path for data transmission between different nodes, and also to avoid interference between adjacent wireless links. In this section, two routing schemes of HCDCN structure are mainly studied. One is the routing algorithm with only regular links, and the other is the efficient routing algorithm with the rack top link.

Regular link routing algorithm As shown in Fig. 5, the racks in row i and column j in HCDCN are represented as r_{ij}. The identifier can enable the rack to obtain the relative position of any destination rack, and easily obtain the routing path to the destination rack along the regular link.

In this wireless data center, the weight value between adjacent racks is regarded as 1, and the weight value of each path is the same. In this case, it will greatly increase the unnecessary complexity to go through each node in depth search. This section designs an algorithm based on Manhattan distance to reduce the calculation cost.

This section proposes a new multicast routing algorithm, which can determine the next hop based on the identifiers of the source and destination rack. Suppose the current position of a packet is r_S and the destination rack is r_D. When the source and destination node are not adjacent, data transmission can only be performed through the intermediate node. There are a maximum of 5 racks connected to r_S through VLC links, and a maximum of 5 wireless links. After traversing, 5 adjacent racks are obtained, and the Manhattan distances L from the 5 racks to r_D are calculated respectively. The smallest L is put into the intermediate node set $r_n\{\}$ as the intermediate node, then use it as the source node and repeat the above steps until $L=1$. The algorithm is as follows:

Input: Source node $r_S(X_S, Y_S)$; Destination node $r_D(X_D, Y_D)$.
Output: Path(Src, Des).

While $r_S \neq r_D$ do
  Compute: $L=|X_S-X_D|+\frac{1}{2}|(X_S-|Y_S-Y_D|)-X_D|$
  $V=L-1$ // V is the number of intermediate nodes
  if $V=0$
    Path(Src, Des)
  end if
  if $V>0$
    for $i=1$ to 5 do
    $L(r_i)=1=|X_i-X_D|+\frac{1}{2}|(X_i-|Y_i-Y_D|-X_D)|$
    Obtain: r_{n1} // r_n is the r_i of L minimum
    $r_{n1}=r_S$
    end for
   Path(Src, Des)$=r_S-r_n\{r_{n1}+r_{n2}+\ldots\}+r_D$
   end if
 end While
 return *Path*

Algorithm 1. Regular link routing algorithm

For example, in Fig. 5, when $r_S(4,1)$ sends data to $r_D(7,4)$, $Path = L-1 = \sqrt{\frac{1}{2}(7\text{-}4)^2+(4\text{-}1)^2}\text{-}1=2.674=3$. The data from (4,1) to (7,4) needs to pass through intermediate nodes, path is 3 hops.

HRA routing algorithm Compared with the regular routing algorithm, adding the rack top link will greatly reduce the routing time and network delay. After adding the rack top link, it is necessary to evaluate whether the number of hops from the source node to the destination node through the rack top link is less than that through the regular link, or the effect of selecting the rack top link at a certain hop is better. According to the unique properties of the structure, an algorithm based on breadth-first search for the shortest path is proposed (HRA, HCDCN routing algorithm). The algorithm is as follows:

The rack top link can shorten the distance between two racks with Manhattan distance of 3, that is, 3 hops can be reduced by transmitting information through the rack top link. In all racks with a path length of no more than 3 hops to r_{ij}, find a rack to make the Manhattan distance between it and r_{mn}, plus the shortest distance between it to r_{ij}. Their minimum sum, serves as a node on the path from r_{ij} to r_{mn}. Then r_{ij} forwards the packet to the node along the shortest path. In order to implement the three-step greedy routing algorithm, each rack maintaining a routing table to record the nodes can be reached within 3 hops. Each entry in the table represents a rack, including its identifier, the shortest path to the current rack, and the length of the path. The algorithm needs to calculate the Manhattan distance d between these racks and r_n respectively. The rack with the shortest Manhattan distance from r_j will be selected as the next hop routing node of the packet. Among the racks connected to r_j through regular links, there are always racks that are closer than the distance from r_j to r_n, and the rack top link can significantly shorten the path length in 1 hop.

comparison of the three structures, including characteristics of the topology, complexity of routing algorithms, and network performance.

Input: Source node $Src(X_S, Y_S)$; Destination node $Des(X_D, Y_D)$.
Output: Path(Src, Des).

- while ($Src \neq Des$)
  - for i=1 to 3 do
    - S_i // Racks i hops away from $Src(X_S, Y_S)$
    - Compute: $L=|X_S\text{-}X_D|+\frac{1}{2}|(X_S\text{-}|Y_S\text{-}Y_D|)\text{-}X_D|$
    - V=L-1
    - for j=1 to $|S_i|$ do
      - r_i // j-th rack in S_i
      - $L_{jD}=|X_j\text{-}X_D|+\frac{1}{2}|(X_j\text{-}|Y_j\text{-}Y_D|)\text{-}X_D|$
      - $r_{jd}=L_{jD}+i$
    - end for
  - end for
  - $r_{next}=find(r, \min\{r,d\})$
  - P_n // The shortest path from r_s to r_{next} in the routing table
  - $Path(Src, Des)=P+P_n$
  - $r_{next}= Src(X_S, Y_S)$
- end while
- return $Path$

Algorithm 2. HRA routing algorithm

As above, for example, in Fig. 5, when $r_S(4,1)$ sends data to $r_D(11,2)$, $Path = L-1 = \sqrt{\frac{1}{2}(11\text{-}4)^2+(2\text{-}1)^2\text{-}1}=4.049=4$. The data from (4,1) to (11.,2), path is 4 hops.

Analysis of experimental results

In this chapter, HCDCN is experimentally compared with Mesh [25] and OWCells [26]. Mesh structure is one of the most popular data center network topologies. In the regular mesh topology, each node in the network is connected with two neighbors in each dimension. OWCells structure uses optical wireless communication to connect racks arranged in regular polygon topology, and uses rack units arranged in regular polygons as basic blocks to build data center network. This section uses the network simulation software OPNET Modeler 14.5 to realize these three structures.

In the experiment in this section, the source server and destination server are randomly selected and mapped to the corresponding *ToR*. Only inter-rack traffic of servers is considered, because intra-rack traffic will not pass through the links in the topology. Set the distance between two adjacent racks to $1m$, and set the unified transmission bandwidth of each VLC link to $10Gbps$. The delay time of optical circuit switching is assumed to be $1ms$. The following is a performance

Performance analysis

Theorem 4.1

HCDCN is represented by $C(M,N,S)$, where M is the number of racks, N is the number of extended layers, and S is the number of servers in each rack. The relationship between the number of expansion layers and the number of racks is $M=3N(N+1)+1$, and the number of servers is $M \times S$。

Proof As shown in Fig. 5, each rack is regarded as a node, when $N=0$, $M=1$; $N=1$, $M=7$; $N=2$, $M=19$; $N=3$, $M=37$. We can deduce the general term formula of M as $M=3N(N+1)+1$. The number of servers in each rack is uniform, so the number of servers is $M \times S$。

Theorem 4.2

The network diameter of HCDCN structure is $d=2N+3$.

Proof Network diameter refers to the maximum value of the shortest path between any pair of servers in the network. According to the construction process of HCDCN structure, the network diameter is determined by two servers located in different layers, and is only related to the number of layers N of HCDCN. In an N-layer HCDCN structure, the maximum distance between any two nodes in the same layer is $N+1$, and different layers are connected in a complete graph. Therefore, the maximum value of the shortest path between any pair of servers in the NCDCN structure is $2(N+1)+1$.

Theorem 4.3
The number of server rack ports in the HCDCN structure is always 7.

Proof The number of server ports in the HCDCN structure will not increase with its expansion, but a fixed constant. When expanding the server-centric network structure, the server needs to be upgraded continuously, which will greatly increase the cost, and the scalability will also be limited by the number of server ports. Although the number of server ports in some topologies is also fixed, there are fewer links between the structures, resulting in poor fault tolerance. The HCDCN structure increases the routing efficiency and fault tolerance of the structure by increasing the links between the servers.

Theorem 4.4
The equal bandwidth of HCDCN structure is $BW_D=(n+2)^2/4$.

Proof The bisection bandwidth refers to the minimum number of edges along the cut when a network is divided into two equal parts. The greater the bisection bandwidth is, the better the stability of the network structure will be. As an important index to evaluate network performance, bisection bandwidth is mainly used to reflect the stability of network topology, which is marked as BW_{num}. The node set G of topology T is divided into two subsets and G_1 and G_2. When the following conditions are met, the network structure T is divided equally: (1)$|G_1 \cap G_2|=0$, (2)$|G_1 \cup G_2|=G$, (3)$||G_1|-|G_2|| \leq 1$. For a complete graph with N nodes, the calculation of bisection bandwidth can be divided into two cases: when N is even, $BW=N^2/4$, and when N is odd, $BW=(N^2-1)/4$. According to the construction rules of the HCDCN structure, each rack can be regarded as a node, and the interior of the rack can be regarded as a whole. In this way, the whole structure can be regarded as a complete graph, which is convenient to calculate the HCDCN structure using the bisection bandwidth calculation method of the complete graph. It can be seen from the previous that the HCDCN structure is a cluster that is expanded according to the number of layers. Considering the definition of bisection bandwidth, we choose to cut off the connection between different layers. The bisection bandwidth of the HCDCN structure can be calculated by the complete graph method. When it expands one layer, the bisection bandwidth increases by 2, that is, $BW_D=(n+2)^2/4$, and n is the number of extended layers.

Theorem 4.5
The space utilization of HCDCN structure is $W=\frac{M}{S}=1.32$. M is the number of server racks, and S is the floor area.

Proof For convenience of statistics, we calculate the HCDCN space utilization rate within $100m^2$. In order to ensure the bandwidth rate and routing efficiency in the actual deployment, the distance between adjacent racks is set to $1m$. According to Fig. 5, the distance between each column of nodes is $1m$, and the distance between each row of nodes is $\frac{\sqrt{3}}{2}m$. Therefore, a maximum of 132 server racks can be placed per $100m^2$. The space utilization rate of HCDCN structure is 1.32.

Topological property evaluation

HCDCN has a parametric design space. Increasing the number of servers in each rack will lead to vertical expansion, so the number of layers N of HCDCN topology can be reduced without changing the total number of servers, because fewer racks are required. On the other hand, reducing the number of servers per rack means that more racks (horizontal expansion) are needed to achieve the required data center network size. In this experiment, the influence of vertical and horizontal expansion of HCDCN on its performance was studied.

Adjust the number of servers in each rack from 15 to 30, with each increase of 5. Figure 7 describes the network performance of HCDCN in 4 different scales. With the fixed size of traffic scale, the performance of HCDCN decreases as the number of servers in each rack increases. The results are the same for the 4 different sizes of HCDCN, but the overall flow increases with the growth of size. Throughput represents the number of successful data transfers per unit of time. Under different traffic scales, the average throughput of the HCDCN structure increases with increasing traffic, indicating better performance of the structure.

Average path length

This section compares the average path length of HCDCN with Mesh and OWCells. The average path length is the average length of the shortest path between all node pairs. We choose Dijkstra algorithm to determine the shortest path length from each node to all other nodes, and calculate the average length of all paths, and compare with the HRA routing algorithm proposed in this paper. Figure 8 shows the shortest path length under different network sizes.

It can be concluded from the experiment that the average path length of the network structure increases linearly with the growth of the network size. In all network sizes, the shortest path length of HCDCN is shorter than Mesh, with an average reduction of about 68%. Moreover, the average

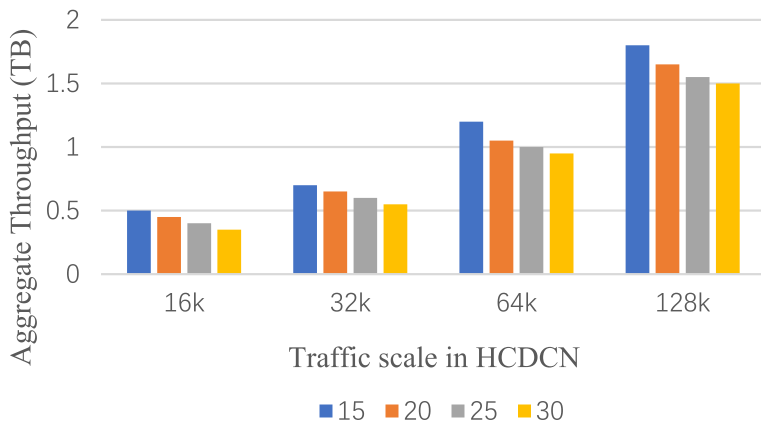
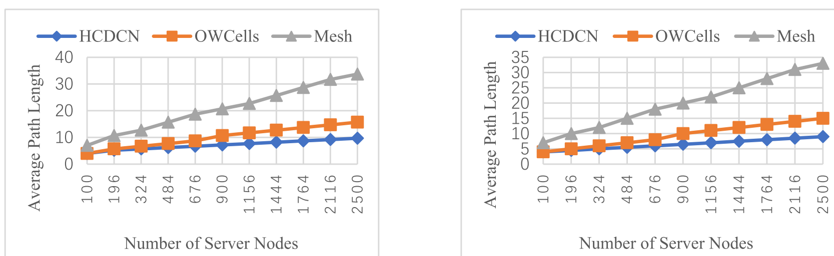


Fig. 7 Aggregate throughput of racks with different number of servers in HCDCN at different scales



(a)Average path length under Dijkstra algorithm (b)Average path length under HRA algorithm

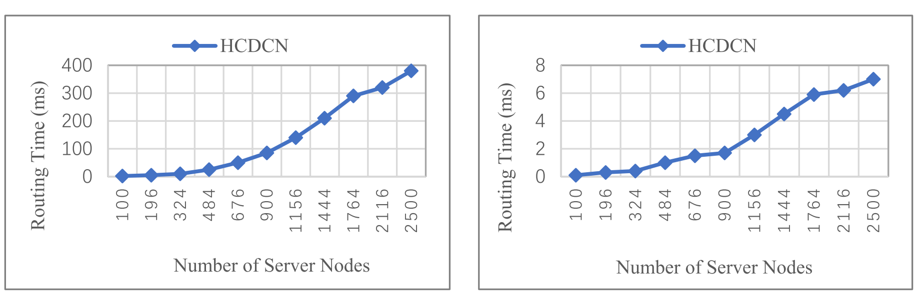
Fig. 8 Average network path length under two algorithms

path length of the HCDCN structure under the HRA algorithm is 9% lower than that of Dijkstra. The average path length represents the average distance between any two nodes, and the smaller average path length indicates a more stable network. As shown in Figure 9, the average path length under the HRA algorithm is smaller than Dijkstra, indicating that the smaller the average path length of the HRA algorithm network, the more stable the connectivity.

By comparing the routing time consumed by HRA algorithm and Dijkstra algorithm, although the two routing algorithms have a similar growth trend when the network scale is expanded, it can be seen that the time consumed by the two algorithms is not in the same order of magnitude. Because Dijkstra algorithm has more search times, the time consumption is very high. The shorter the routing time, the faster the algorithm responds and the faster the data processing. The HRA routing algorithm can effectively reduce routing time and increase data transmission speed.

Network throughput and network delay

Compare the network performance of HCDCN with Mesh and OWCells by using two indicators of network



(a)Dijkstra algorithm routing time (b)HRA algorithm routing time

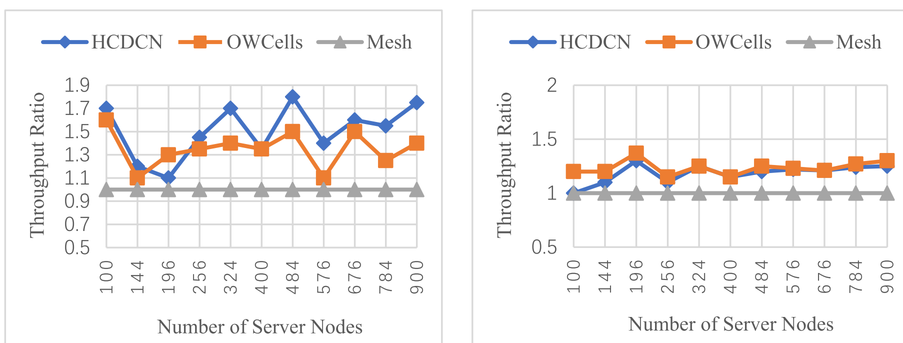
Fig. 9 Routing time under two algorithms throughput and network delay. Mesh is a regular grid topology, and the network throughput is described as the ratio of the actual network throughput between HCDCN and Mesh under two traffic modes. The experiment selects uniform random traffic, and sets the average size of the data flow to 4*Mb* and 12*Mb* respectively. In the experiment, the source node and destination node of each data flow are randomly selected.

Set the traffic to 4Mb and increase the number of racks from 100 to 900. As shown in Fig. 10(a), the throughput of HCDCN is 1.8 times larger than Mesh on average. When the traffic increases to 12Mb, the actual throughput of all three networks shows a large increase. For the three network structures, the throughput shows an increasing trend, that is the load has not yet reached the bottleneck of the network.

As shown in Fig. 11, when the traffic is 4*Mb*, the delay increases steadily with the increase of network size, and the gap between different networks increases with the increase of network size. When the traffic increases to 12*Mb*, the latency of the three networks increases correspondingly, but the HCDCN is still lower than the other two structures. Network delay is also called average data delay, which refers to the total time delay experienced by data from the source node to the destination node to receive information and confirm. The smaller the network delay, the faster the data transmission. Under the same scale, the delay of the HCDCN structure is the lowest, and the response is timely.

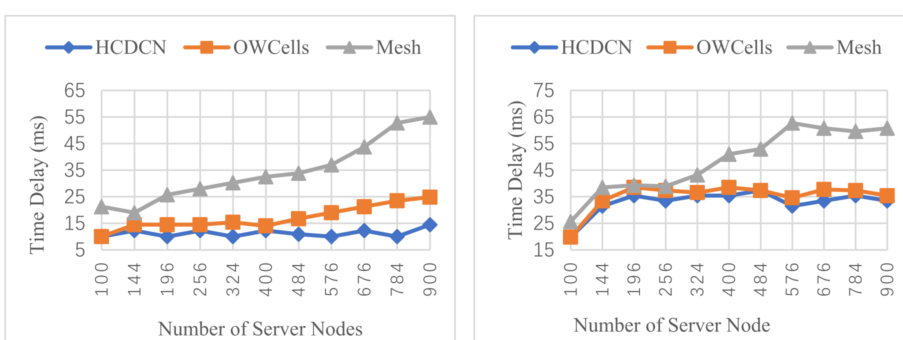
Conclusions

In order to improve the insufficient bandwidth and poor flexibility of the wired data center, as well as the low connectivity and routing efficiency of wireless data center network structure based on millimeter wave, when designing the data center network structure, this paper introduces a promising wireless communication alternative: wireless communication technology based on LED visible light. And wireless data center network topology HCDCN based on visible light communication is designed. Because the traditional server rack



(a)Average traffic size 4Mb (b)Average traffic size 12Mb

Fig. 10 Throughput under uniform random traffic



(a)Average traffic size 4Mb (b)Average traffic size 12Mb

Fig. 11 Delay under uniform random traffic is insufficient in access, this paper first transforms the server rack, uses the hexahedral structure, places it in a honeycomb structure, and installs the rack top link on the top of the rack to increase the degree of the server node and improve the communication efficiency. For this reason, a routing algorithm is designed to make the selection of regular links and random links more efficient in data transmission. Finally, the topological properties and network performance of HCDCN are evaluated through experiments, and the advantages of its algorithm in improving routing efficiency and reducing delay are verified. The new wireless data center network based on visible light wireless communication technology proposed in this paper could largely alleviate the hot spot congestion of servers in large traffic data centers and provided higher bandwidth.

Acknowledgements
This work was supported by the Special Project for Key R&D and the Promotion of Science, Technology Department of Henan Province (222102210272, 222102210055 and 232102211009), the Postgraduate Education Reform and Quality Improvement Project of Henan Province under Grant (YJS2022JD26), the Major Science and Technology Projects of Henan Province, and the Major Public Welfare Projects of Henan Province (201300210400), Kaifeng Science and Technology Development Plan (2201010).

Authors' contributions
QZ provides innovative points for research, constructs the structure of the paper, provides mathematical theoretical methods for the paper, and writes the paper. XD provides experimental proof for the paper. JL provides data set support for the paper.ZH polished and revised the paper. All authors reviewed the manuscript.

Funding
National Natural Science Foundation of China (61672209).

Availability of data and materials
The original contributions presented in the study are included in the article material, further inquiries can be directed to the corresponding author/s.

Declarations

Ethics approval and consent to participate
No human and animal studies are presented in this manuscript.

Competing interests
The authors declare no competing interests.

Received: 30 March 2023 Accepted: 8 November 2023
Published online: 25 November 2023

References
1. Mansouri Y, Toosi AN, Buyya R (2017) Data storage management in cloud environments: taxonomy, survey, and future directions. ACM Comput Surv (CSUR) 50(6):1–51
2. Tsiknas KG, Aidinidis PI, Zoiros KE (2021) Performance evaluation of transport protocols in cloud data center networks. Photon Netw Commun 42(2):105–116
3. Zhang J, Yu FR, Wang S et al (2018) Load balancing in data center networks: a survey. IEEE Commun Surv Tutorials 20(3):2324–2352
4. Sharma V, Mishra R (2020) A comprehensive survey on data center network architectures[C]. 2020 8th International Conference on Reliability, Infocom Technologies and Optimization (Trends and Future Directions) (ICRITO) pp. 222–228
5. Greenberg A, Hamilton JR, Jain N et al (2009) VL2: a scalable and flexible data center network. Proceedings of the ACM SIGCOMM 2009 conference on data communication. pp 51–62
6. Guo C, Wu H, Tan K et al (2008) Dcell: A scalable and fault-tolerant network structure for data centers. Proceedings of the ACM SIGCOMM 2008 conference on Data communication. pp 75–86
7. Li D, Guo C, Wu H et al (2009) FiConn: Using backup port for server interconnection in data centers[C]. IEEE INFOCOM 2009:2276–2285
8. Guo C, Lu G, Li D et al (2009) BCube: a high performance, server-centric network architecture for modular data centers. Proceedings of the ACM SIGCOMM 2009 conference on Data communication. pp 63–74
9. Li W, Liu J, Wang S et al (2021) Survey on traffic management in data center network: from link layer to application layer. IEEE Access 9:38427–38456
10. Zhou X, Zhang Z, Zhu Y et al (2012) Mirror mirror on the ceiling: flexible wireless links for data centers. ACM SIGCOMM Comput Commun Rev 42(4):443–454
11. Hall MN, Foerster KT, Schmid S et al (2021) A survey of reconfigurable optical networks. Opt Switch Netw 41:100621
12. Hamza AS (2019) Recent advances in the design of optical wireless data center networks. Broadband Access Commun Technol XIII 10945:114–124
13. Celik A, Shihada B, Alouini MS (2018) Wireless data center networks: Advances, challenges, and opportunities arXiv preprint arXiv
14. Qunji H (2017) Application of wireless technology in data center. Intell Building 1:19–21
15. Yuang M, Tien PL, Ruan WZ et al (2020) OPTUNS: Optical intra-data center network architecture and prototype testbed for a 5G edge cloud. J Opt Commun Netw 12(1):A28–A37
16. Buscaino B, Chen E, Stewart JW et al (2020) External vs. integrated light sources for intra-data center co-packaged optical interfaces. J Lightwave Technol 39(7):1984–1996
17. Zhao S, Zhu Z (2020) On virtual network reconfiguration in hybrid optical/electrical datacenter networks. J Lightwave Technol 38(23):6424–6436
18. Xue X, Prifti K, Pan B et al (2021) Automatically reconfigurable optical data center network with dynamic bandwidth allocation. J Opt 23(11):114003
19. Tsai CT, Cheng CH, Kuo HC et al (2019) Toward high-speed visible laser lighting based optical wireless communications. Prog Quantum Electron 67:100225
20. Qin Y, Guo D, Lin X et al (2019) Design and optimization of VLC enabled data center network. Tsinghua Sci Technol 25(1):82–92
21. Qin Y, Guo D, Luo L et al (2019) Design and optimization of VLC based small-world data centers. Front Comput Sci 13:1034–1047
22. Cao B, Zhao J, Yang P et al (2019) Multiobjective 3-D topology optimization of next-generation wireless data center network. IEEE Trans Industr Inf 16(5):3597–3605
23. Zhang C, Wu F, Gao X et al (2017) Free talk in the air: a hierarchical topology for 60 GHz wireless data center networks. IEEE/ACM Trans Netw 25(6):3723–3737
24. Luo L, Guo D, Wu J et al (2016) VlCcube: a VLC enabled hybrid network structure for data centers. IEEE Trans Parallel Distrib Syst 28(7):2088–2102
25. Shahdad S Y, Sabahath A, Parveez R (2016) Architecture, issues and challenges of wireless mesh network[C]. 2016 International Conference on Communication and Signal Processing (ICCSP). pp. 0557–0560
26. Hamza A S, Yadav S, Ketan S, et al (2017) OWCell: Optical wireless cellular data center network architecture[C]. 2017 IEEE International Conference on Communications (ICC). pp. 1–6

Publisher's Note