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An Efficient Wireless Control Plane for Software Defined Networking in Data Center Networks

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ABSTRACT Software defined networking (SDN) has re-defined the way data center networks are deployed and functioned. The ability to separate the control plane and data plane have led to the simpler design and easier management. In SDN, the data plane and control plane are separately managed, so building an additional wired network to connect the control plane and the data plane can lead to a high cabling complexity. This paper proposes an end-to-end end wireless control plane architecture for SDN-enabled data center networks. In the proposed architecture, the switches form clusters that are wirelessly connected to the controller via access points (APs) and relay nodes (RNs). The switches use the 2.4/5-GHz band to connect with the APs, whereas the APs and the RNs are connected to the controller using the 60-GHz band. We have presented an analytical model to derive achievable data rates in our wireless control plane. We have also proposed two algorithms that allow an optimal number of a cluster size of the switches to be connected with the Controller via minimum number to APs/RNs such that the control traffic demands of the switches is guaranteed in interference constrained environment. Through extensive simulations, the results of our proposed architecture show that the cabling complexity in the control plane is reduced to zero and additional switches may be easily added in SDN data center. Thus, a pure wireless solution for building a control plane in a data center network is feasible.

INDEX TERMS Data center networks, software-defined networks, wireless control plane.

I. INTRODUCTION

Traditional data center networks require switches to perform control functions such as routing in a distributed manner. Software-defined networking (SDN) decouples the control plane from the data plane and centralizes the control plane via a controller [1]. This allows each switch to only keep data plane functions such as packet switching. With SDN, network management has become easier and dynamic with the help of centralized and programmable control [2]. To separate the traffic of control plane from the data plane, a separate physical network is required to connect all switches to the controller. However, it is an intricate task to build such a dedicated wired network for the control plane [3]. It may incur enormous cabling effort to ensure the full connectivity between the all switches and the controller [4].

Recent studies on data center architectures propose wireless solutions to interconnect the switches instead of using cables [5]. There are two major candidate technologies for wireless data centers: Free Space Optics (FSO) and Radio Frequency (RF) links [6]. Extensive research has been dedicated to augmenting the traditional data centers with wireless capability using these two candidate technologies [6]–[16]. There are two main reasons of why these existing schemes cannot be directly applied to the formation of wireless control plane in SDN data center. First, these schemes propose wireless solutions for data planes where the interconnection is between switches rather than switches being connected to the Controller. Secondly, the data traffic volume is usually very high compared to low control traffic demands. Therefore, in this paper, we propose an end-to-end wireless network architecture for connecting the switches to the Controller in a control plane when deploying SDN in data center networks.

In a control plane of SDN data center, it is required to connect all switches to the SDN Controller. In order to build a wireless network connecting all switches to the SDN controller, we need to equip each Top of Rack (ToR) switch...
with wireless radio(s). The controller is also equipped with wireless radios. As there are thousands of ToR switches in a data center network, many ToR switches may not be able to make a direct connection to the controller. Moreover, the throughput between the ToR switches and Controller may not be satisfied due to the poor signal strength if we make long distance wireless links from switches to the Controller.

To address the aforementioned issues, we propose a pure wireless control plane architecture, as shown in Fig. 1. The ToR switches are grouped into clusters and each cluster is connected to an AP using directional antennas. The APs are connected to the controller via RNs. The switches communicate with the APs using frequency $f_1$ which is 2.4/5 GHz. The APs/RNs communicate with the controller using frequency $f_2$ which is 60 GHz.

FIGURE 1. Switches in a data center are divided into clusters and each cluster is connected to an AP using directional antennas. The APs are connected to the controller via RNs. The switches communicate with the APs using frequency $f_1$ which is 2.4/5 GHz. The APs/RNs communicate with the controller using frequency $f_2$ which is 60 GHz.

The aim of this work is to minimize the number of APs and RNs that helps to determine the number of APs or the cluster size of the ToR switches and the placement of APs in the network. Two algorithms are proposed for the wireless control plane architecture. The first one is the AP placement algorithm and the second one is the RN placement algorithm. Through extensive simulations, we demonstrate that a reasonable number of APs and RNs are required to support the control traffic demand of all the ToR switches in our proposed architecture.

The rest of the paper is organized as follows. In Section II, the related work is discussed. In Section III, we present the system model and our problem formulation. In Section IV, the algorithms for AP and RN placement are given. In Section V, we present the simulation settings and the performance evaluation results. Finally, Section VI concludes the paper.

II. RELATED WORK

There have been some studies working on wireless data center networks. In [7], Shin et al. investigated the feasibility of wireless data center networks by using 60 GHz radios. The authors suggested a cylindrical design for the switch rack and construct a topology through Cayley graphs so that all the switches are interconnected to each other.

In another work [10], Halperin et al. used 60 GHz links for inter-rack communication. The authors suggested that by using 60 GHz directional links, concurrent multi-Gbps data rates can be achieved. In a similar work [9], the authors also used 60 GHz link with 3D beam forming to reduce interference.

In this work, the authors focused on link blockage and link interference problems to increase overall link range and number of concurrent transmissions.

In another work [11], Zhu et al. suggested a facilities network which is connected to ToR switches through 60 GHz beamforming wireless links. Here the facilities network is mainly used for issues like link coordination, link interference and reporting network failures. In their proposed architecture, a number of low-latency control links can concurrently work to exchange control messages. Zhang et al. [17] mainly focused on the propagation distance using 60 GHz radios in data centers. The suggested architecture, Graphite, makes the best use of the propagation distance by connecting several servers among each other, which is not the case in existing studies on 60 GHz wireless data centers. They also built a testbed to evaluate their design.

A ring shaped architecture is suggested in [18] to enable a large number of concurrent wireless transmissions within a data center network. The authors suggested 3D ring reflection spaces (RRSs) deployment that inherits a precise reflection method to interconnect a number of wireless links. Their proposed RRSs architecture also reduces wireless interference.

In [8], Hamedazimi et al. suggested a dynamic reconfigurable design for data center networks. In this work, the authors proposed a wireless network in which Free Space Optic (FSO) links are installed for inter-rack communication. To the best of our knowledge, none of these studies
adequately addresses the problem of building a wireless control plane for deploying SDN in data center networks.

Our work is an extension of our previous work presented in [3] and [19] where a semi-wireless control plane design is proposed. Xie et al. [3] and Umair et al. [19] proposed to connect the ToR switches with the controller via APs. The switches are connected to the APs using wireless channels and the APs are further connected to the controller using cables. The authors have presented an analytical design to calculate the cluster size of the switches. In this paper, we propose a completely wireless control plane design for software-defined data center networks. We propose to use two frequency bands at the same time. The 2.4/5 GHz directional antennas are used for the communication between the switches and the APs, whereas 60 GHz directional antennas are used for the communication between the APs/RNs and the controller. Therefore, in this work we minimize the number of APs and RNs for deploying a completely wireless control plane in a data center network.

III. SYSTEM MODEL AND PROBLEM FORMULATION

In this section, we first present the system model and then formulate the problem of placing access points (APs) and relay nodes (RN) in the network. The goal is to build a wireless network that connects the ToR switches with the controller in a control plane of a SDN-enabled data center network. In the wireless network, all the ToR switches can communicate with the Controller through wireless channels while the control traffic demand of all the ToR switches is satisfied.

A. SYSTEM MODEL

Suppose that we are given a data center network. As shown in Fig. 1, the data center network consists of a set of ToR switches denoted by \( S \), a set of APs denoted by \( A \), a set of RNs denoted by \( R \), and a controller \( C \). Each ToR switch \( s_i \in S \) has a fixed location. Associated with each ToR switch is its control traffic that is to be sent to the SDN controller. Usually the control traffic is bursty in nature, so it is assumed that all the ToR switches in the network have the maximum control traffic demand of \( \lambda \). In order to build a wireless control plane, we first divide the ToR switches into equal-sized square-shaped clusters. The ToR switches in one cluster are connected to one AP, which is placed at the geographic center of the cluster and at a height. The switch antennas are installed such that they face upward towards the AP. Each AP, denoted by \( a_j \in A \), is further connected to the controller using wireless links either directly or via RNs. If an AP is out of the transmission range of the controller, then a RN is used to connect the AP to the controller. A RN, denoted by \( r_k \in R \), can only be placed at given candidate locations in the data center.

The wireless control plane network consists of two components: an access network and a backbone network. In the access network, all the ToR switches communicate with the APs, whereas the backbone network consists of the connections from the APs/RNs to the controller. All the ToR switches, APs, RNs and the controller are equipped with directional antennas as shown in Fig. 2. In the access network, each AP receives the control traffic from the ToR switches using 2.4/5 GHz band. In the backbone network, this aggregated traffic from each AP is transmitted to the next hop (a RN or the controller) using 60 GHz band. The reason we use 60 GHz for the backbone network is to reduce the interference between the access and backbone networks of the wireless control plane. We assume that the APs and the RNs use a beamforming technique to increase the transmission distance and to reduce the interference. With the beamforming technique, an array of antennas is installed on each AP or each RN. These multiple antennas installed on the same AP/RN will direct the beam in one direction to increase the transmission distance and throughput [20].

In order to avoid wireless transmission collisions, multiple access technologies are employed for the switches within the same cluster. We use Time-Division Multiple Access (TDMA) to schedule packets sent from the ToR switches to the APs. We use Orthogonal Frequency-Division Multiple Access (OFDMA) for the communication between the APs/RNs and the controller. OFDMA supports multiple orthogonal channels and thus simultaneous connections from the APs/RNs to the controller can be supported. We use physical interference model to analyze the maximal throughput of the network. The nodes that transmit concurrently and use the same channel can cause interference to each other. For simplicity, we evaluate the wireless capacity of one controller for uplink transmission only. However, the same model can be easily applied to the case of downlink transmission.

To begin with placing the minimal number of APs and RNs, we need to compute the maximal data rate of ToR switches, APs and RNs supported by wireless channels. To determine the maximal throughput (i.e., the wireless data rate) of a ToR switch, we need to compute the Signal to Interference Noise Ratio (SINR). By definition, SINR is given in Eq. (1) as follows:

\[
\text{SINR} = \frac{P_s}{\zeta + N_o}.
\] (1)
where $P_s$ is the signal power of a ToR switch, $\zeta$ is the interference power and $N_o$ is the background noise. We first compute the signal power and the interference power for the communication from the ToR switch to the AP in its cluster. For this goal, we need to determine the path loss of a transmission from ToR switch $s_i$ to AP $a_j$. The path loss of the transmission from ToR switch $s_i$ to AP $a_j$ can be computed using the Shannon Hartley Equation [22], which is given as follows:

$$\rho_{ij} \geq 20 \log f_{ij} + 10 \log d_{ij} + P_f(n) - 28,$$  \hspace{1cm} (2)

where $f_{ij}$ is the frequency of operation between ToR switch $s_i$ and AP $a_j$, $k$ is the path loss exponent ranging from 2 to 4, $d_{ij}$ is the distance between ToR switch $s_i$ and AP $a_j$. $P_f(n)$ is the floor loss penetration factor (which is 0 in our data center network). The path loss given in Eq. (2) may increase due to other factors such as reflection from metal frames and signal absorption in walls of the data center. The signal power at AP $a_j$ from ToR switch $s_i$ is thus derived as follows:

$$P_{ij} = \frac{P_i}{\rho_{ij}},$$  \hspace{1cm} (3)

where $P_i$ is the transmission power of a ToR switch antenna.

Next, we compute the interference power on link $l_{ij}$ from the ToR switch $s_i$ to the AP $a_j$. As we use TDMA within one cluster, the interference can only be caused by simultaneous transmissions from the other clusters. The interference power is thus formulated as follows:

$$\xi(l_{ij}) = \sum_{s_r \in S_j} P_{rj} = \sum_{s_r \in S_j} \frac{P_{rj}}{\rho_{rj}},$$  \hspace{1cm} (4)

where $s_r$ are the ToR switches that interfere with the link $l_{ij}$ and $S_j$ is the set of ToR switches connected to AP $a_j$.

The SINR of the link $l_{ij}$ can now be calculated as follows:

$$\text{SINR}_{ij} \approx \frac{(P_i/\rho_{ij})G_i}{\sum_{s_r \in S_j} (P_{rj}/\rho_{rj})G_{rj} + N_o},$$  \hspace{1cm} (5)

where $G_i$ and $G_{rj}$ are the gains of transmission and interference respectively for the ToR switch $s_i$, $N_o$ is the noise factor whose value is small enough to be ignored.

The achievable data rate of a ToR switch $s_i$ when TDMA scheme is employed can now be computed as:

$$\lambda_i \approx \frac{\text{SINR}_{ij} \cdot B_j}{E_b/N_o |S_j|},$$  \hspace{1cm} (6)

where $B_j$ is the wireless channel capacity of the AP $a_j$ computed using Shannon Hartley Equation [22], $E_b/N_o$ is the Bit Energy to Noise ratio. $|S_j|$ is the number of ToR switches connected to AP $a_j$.

After the achievable data rate of ToR switch is determined, we now compute the achievable wireless data rate of the APs and the RNs. As we use OFDMA in the backbone network, it is assumed that a set of orthogonal channels with a collective subcarrier bandwidth is allocated to each AP and RN. We propose to use a beamforming technique to focus the transmission of an AP in one direction. This provides enough bandwidth to transmit the control traffic from the ToR switches to the controller.

In order to compute the achievable data rate of the APs and the RNs, we compute the SINR between APs/RNs and the controller using the Log Distance Path Loss Model [23]. The achievable data rate of an AP $a_j$ can be formulated as follows:

$$\alpha_j \approx \frac{\text{SINR}_{jc} \cdot B_c}{E_b/N_o},$$  \hspace{1cm} (7)

where $\text{SINR}_{jc}$ is the SINR achieved between AP $a_j$ and the controller $C$. $B_c$ is the wireless sub-carrier transmission bandwidth allocated to the AP. The achievable data rate of a RN can be computed as follows:

$$\gamma_k \approx \frac{\text{SINR}_{kc} \cdot B_k}{E_b/N_o},$$  \hspace{1cm} (8)

where $\text{SINR}_{kc}$ is the SINR between RN $r_k$ and Controller $C$. Once the achievable data rates are determined, we can formally define the problem of placing APs and RNs in the next subsection.

**B. PROBLEM FORMULATION**

The problem of our concern is to place the minimal number of APs and RNs that can satisfy the traffic demand between the ToR switches and the controller and their full connectivity is guaranteed. The problem of placing APs and RNs is formulated as follows:

$$\text{min. } |A| + |R|,$$  \hspace{1cm} (9)

s.t. $\lambda_i \geq \lambda$,  \hspace{1cm} (10)

$$\alpha_j \geq \sum_{s_r \in S_j} \alpha_{s_r},$$  \hspace{1cm} (11)

$$\gamma_k \geq \sum_{a_j \in A_k} \alpha_{a_j} + \sum_{r_j \in R_k} \gamma_{r_j}.$$  \hspace{1cm} (12)

In Eq. (10), it is specified that the achievable data rate of a ToR switch should be greater than or equal to its control traffic demand. The constraint in Eq. (11) states that the placed AP should meet the cumulative traffic demand of all the ToR switches in its cluster. Finally, Eq. (12) means that the RN should meet the cumulative demand of all the APs and RNs connected to that RN, where $A_k$ and $R_k$ denote the set of APs and the set of RNs respectively, which are connected to RN $r_k$.

In the next section, we propose two algorithms that respectively place the minimal number of APs and the minimal number of RNs. Meanwhile, our algorithms guarantee that the control traffic demand of all the ToR switches is met and all the ToR switches can communicate with the controller through the wireless network.

**IV. SOLUTION**

In this section, we propose two algorithms. Algorithm 1 is to place the minimal number of APs to cover all the ToR
Algorithm 1 AP Placement Algorithm

Input: The set of ToR switches denoted by $S$, the control traffic demand of each ToR switch $\lambda$, the wireless channel capacity of each AP $B_i$.

Output: The locations of APs;

1: $S_{\text{min}} = 1$;
2: $B_i = \frac{B_i}{\lambda}$;
3: while $S_{\text{min}} \neq S_{\text{max}}$ do
   4: $S_{\text{tmp}} = \left[\text{average}(S_{\text{min}}, S_{\text{max}})\right]$;
   5: Divide $S$ in clusters of size $S_{\text{tmp}}$;
   6: Place AP at the center of each cluster;
   7: Compute max $\lambda_i^*$ among all clusters by Eq. 6;
   8: if $\lambda_i^* \geq \lambda$ then
      9: $S_{\text{min}} = S_{\text{tmp}} + 1$;
   10: else if $\lambda_i^* < \lambda$ then
      11: $S_{\text{max}} = S_{\text{tmp}} - 1$;
   12: end if
3: end while
14: Return cluster size $S_{\text{tmp}}$ and locations of APs;

switches by computing the maximal cluster size. Whereas Algorithm 2 aims to place the minimal number of RNs that connects all the APs to the controller.

A. PLACEMENT OF ACCESS POINTS

In the AP Placement algorithm, we place the minimal number of APs by assigning the maximal number of ToR switches to an AP, so that the control traffic demand of all switches can be met. The ToR switches are clustered and an AP is placed at the center of each cluster. The maximal cluster size is computed through a modified binary search algorithm. The cluster size computed through Algorithm 1 may not equally divide the whole data center, so the ToR switches at the borders of the data center may form clusters with less number compared to the maximal cluster size. In our proposed algorithm, each cluster is square in shape. If the cluster size can not form a square shape, we select the cluster shapes that are closest to square shape. This can be achieved by computing the width-to-length ratio for all possible combinations of the cluster size. Once the maximal cluster size is determined, the data center can be divided into equal sized clusters and the APs are placed at the center of the clusters.

The details of our AP Placement algorithm are given in Algorithm 1. We begin by initializing the minimum cluster size, $S_{\text{min}} = 1$. The maximum cluster size is set to the number of ToR switches each AP can support with its maximum wireless channel capacity $B_i$, i.e., $S_{\text{max}} = \left\lfloor \frac{B_i}{\lambda} \right\rfloor$. Then we run a modified binary search to compute the maximal cluster size that satisfies the control traffic demand of the ToR switches. The cluster size, denoted by $S_{\text{tmp}}$, is iteratively computed. The maximum achievable data rate among the ToR switches in all clusters is also computed until the control traffic demand of each ToR switch is satisfied. Once the cluster size that satisfies the control traffic demand is obtained, we place an AP at the center of each cluster based on that cluster size. The location of each cluster center is obtained by calculating the centroid of the locations of the corner ToR switches. This algorithm returns the maximal cluster size of the ToR switches and the locations of the APs.

In Algorithm 1, the APs are placed such that the control traffic demand of all the ToR switches is satisfied. But the algorithm still does not guarantee the full connectivity of the network by connecting all the APs to the controller. It is possible that some of the APs cannot make a direct connection with the controller. For these APs, we need to place RNs at certain locations among the given candidate locations in the data center to connect them to the controller. In Algorithm 2, we place the minimum number of RNs in the candidate locations such that the full connectivity of the network is guaranteed and bandwidth requirements are met.

Algorithm complexity: In order to obtain the optimal cluster size $S_{\text{tmp}}$, Algorithm 1 performs a binary search over the range $[1, \lfloor B_i/\lambda \rfloor]$, as it is shown from line 3 to line 13. The run time complexity for the binary search is $\log \lfloor B_i/\lambda \rfloor$. In each step of the binary search, we need to find a cluster shape based on the cluster size $S_{\text{tmp}}$, as it is shown in line 5. Each cluster is a square whose size can be denoted by $x^2$. We can find the maximal $x$ while satisfying $x^2 \leq S_{\text{tmp}}$. The complexity for computing the cluster shape in line 5 is linear. In summary, the run time complexity of Algorithm 1 is $O(\log \lfloor B_i/\lambda \rfloor)$.

B. PLACEMENT OF RELAY NODES

Suppose that we are given a set of candidate locations for placing the RNs, denoted by $R_{\text{CL}}$. In Algorithm 2, we place the minimal number of RNs to satisfy the bandwidth and connectivity requirements of the control plane. We only need to connect the APs that are out of the transmission range of the controller by using RNs. Let $A'$ denote the set of APs, $A' \subseteq A$, that are out of the range of the controller. Our algorithm has two steps. The first step is to use the minimal number of RNs to connect all APs in $A'$. We call the RNs that is directly connected to the APs as the edge RNs, denoted by the set $R_e$. Each edge RN $r_k \in R_e$ should meet the capacity constraint to serve the APs that are directly connected to it. The second step is to place more RNs to interconnect all the edge RNs to the controller.

In the first step, we assign a weight to each node in $R_{\text{CL}}$. The weight of a node $r_k$, $r_k \in R_{\text{CL}}$, is defined as the number of APs within the transmission range of $r_k$. Each time, we select the $r_k^* \in R_{\text{CL}}$ with the highest weight to place a RN in the location of $r_k^*$. Then, we connect as many APs as possible to this new RN until it reaches its capacity $y_k$. This operation is repeated until all APs in $A'$ are connected to the edge RNs.

At the end of the first step, we have a set of edge RNs and the controller. The aim of the second step is to place the minimal number of RNs in the rest of the candidate locations to interconnect all the edge RNs to the controller. To solve this problem, we build a backbone tree $T$. To initialize the process, we start by connecting the furthest edge relay node $r_e^*$ to the Controller using the shortest path $P_{r_e^*}$. We then
Algorithm 2 RN Candidate Location Selection Algorithm

**Input:** $A'$ : Set of APs out of range of C; $R_{CL}$ : Set of candidate locations of RNs;

**Output:** $R$ : Set of Selected locations of RNs;

1. $R_e \leftarrow \emptyset$, $A_{imp} \leftarrow A'$;
2. while $A_{imp} \neq \emptyset$
   // Assign APs to $R_e$
   3. Assign weight to each $r_k \in R_{CL}$;
   4. Select $r_k \in R_{CL}$ with the highest weight;
   5. while $\gamma_k^* \leq \gamma_T$
      6. Connect $a_k \in A^*_k$ to $r_k^*$;
      7. $A_k = A_k \cup \{a_k\}$;
      8. $A_{imp} = A_{imp} \cup \{r_k\}$;
   end while
   9. $R_e = R_e \cup \{r_k\}$;
11. end while
12. $R_{mp} \leftarrow R_e$; // Connect Edge RNs to Controller
13. Find the shortest path $P_{r_\gamma}$ from $C$ to $r_\gamma^*$; // $r_\gamma^*$ : Furthest edge RN from $C$
14. $T \leftarrow P_{r_\gamma}$; // Build a backbone tree
15. $R = R \cup P_{r_\gamma}$;
16. $R_{mp} = R_{mp} \setminus \{r_\gamma^*\}$;
17. while $R_{mp} \neq \emptyset$
   18. Find $r_e \in R_{mp}$ that is closest to $T$;
   19. Connect $r_e$ to $T$ with shortest path $P_{r_e}$ under the constraint in Eq. 12;
   20. $R = R \cup P_{r_e}$; // Add all locations of $P_{r_e}$ in $R$;
   21. $R_{mp} = R_{mp} \setminus \{r_e\}$;
22. end while

add all the positions of this path in the list of the selected candidate locations. Next, we connect the remaining edge RNs by connecting the nearest edge RNs to the backbone tree using the shortest path until the constraint in Eq. 12 is satisfied. If the constraint is not satisfied, the edge RNs take another shortest path to the Controller. We add all these locations from these paths to the list of selected candidate locations and place RNs at these locations.

At the end of this algorithm, we determine the set of candidate locations where the RNs should be placed to connect all $A'$ APs to the controller. In the next section, we simulate the proposed algorithm and evaluate the our theoretical results.

**Algorithm complexity:** Algorithm 2 consists of two parts. First, some edge RNs are placed to connect all the APs that are out of the transmission range from the controller, as it is shown from line 2 to line 11. The placement of edge RNs utilizes a greedy algorithm to iteratively place the best RN. Here, the complexity is $O(|A|^2)$, where $|A|$ denotes the total number of APs. Second, additional RNs are placed in the data center to connect all the edge RNs to the controller, as it is shown from line 14 to line 22. A backbone tree is built by iterating over each edge RN and finding a shortest path. The total number of candidate RN locations is denoted by $|R|$. The run time complexity for the second part is thus equal to $O(|R|^3)$. In summary, the run time complexity of Algorithm 2 is equal to $O(|A|^2) + O(|R|^3)$.

V. PERFORMANCE EVALUATION

In this section, we present the simulation settings and then evaluate our algorithms of placing APs and RNs.

A. SIMULATION SETTINGS

We introduce a simple data center network consisting of 4900 ToR switches ($70 \times 70$ racks) as shown in Fig. 3. The ToR switches are installed in the data center and on top of each rack. Each rack measures 1m $\times$ 0.5m. Between each rack is a space of 1m horizontally and 1.5m vertically. APs are installed at a height of 4m from the ToR switches such that the switch antennas face upward to connect with the APs. The RNs are installed at the same plane as the APs. The controller is installed at the ceiling at a height of 9 meters from the ToR switches and 5m from the plane of APs and RNs. The task is to connect the ToR switches to the controller in a way that the control traffic demand of ToR switches is satisfied and the connectivity is guaranteed from ToR switch to the controller using the minimal number of APs and RNs.

Next, we introduce the settings of frequency bands. We simulate with 2.4 GHZ and 5 GHZ bands using TDMA scheme from the ToR switches to the APs. For the communication between the APs/RNs to the controller and the communication between the APs to the RNs, we use 60 GHZ band. The bandwidth for the channel between the ToR switches and the APs is 90 MHZ (2400-2490 MHZ) at 2.4 GHZ band and 160 MHZ (5170-5330 MHZ) at 5 GHZ band. We use the default settings of 802.11ad [24] for all APs and RN. Each AP/RN is allocated a subcarrier transmission bandwidth of 2.15 GHZ and has a wireless channel capacity of 1 Gbps to connect with other APs/RNs. The controller is installed with 5 directional non-overlapping antennas to receive data from the APs and the RNs. Each radio of the controller has a capacity of 1 Gbps.

We simulate the bandwidth for ToR switch antennas of 30°, 60° and 90°. The transmit power of each ToR switch and each AP antenna is -10 dB. We assume equal transmission gains of all switch antennas. As the data center network is indoor and...
TABLE 1. Simulation parameters and values.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of ToR switches</td>
<td>4900</td>
</tr>
<tr>
<td>Rack Size (horizontal axis)</td>
<td>1 m</td>
</tr>
<tr>
<td>Rack Size (vertical axis)</td>
<td>0.5 m</td>
</tr>
<tr>
<td>Inter-rack Space (horizontal axis)</td>
<td>1m</td>
</tr>
<tr>
<td>Inter-rack Space (vertical axis)</td>
<td>1.5m</td>
</tr>
<tr>
<td>Height of AP from ToR switches</td>
<td>4m</td>
</tr>
<tr>
<td>Height of controller from ToR switches</td>
<td>9m</td>
</tr>
<tr>
<td>Control traffic demand of ToR Switches $\lambda$</td>
<td>0.1 - 1 Mbps</td>
</tr>
<tr>
<td>Transmit Power of ToR Switch, AP and RN</td>
<td>-10 dB</td>
</tr>
<tr>
<td>ToR Switch Antenna Beamwidths</td>
<td>$30^\circ$, $60^\circ$ and $90^\circ$</td>
</tr>
<tr>
<td>AP - ToR Switch Bandwidth</td>
<td>90 MHz and 160 MHz</td>
</tr>
<tr>
<td>Subcarrier Bandwidth of AP/RN</td>
<td>2.15 GHz</td>
</tr>
</tbody>
</table>

noisy, we select a path loss exponent of 3 for our simulations. The $E_{b}/N_{0}$ is set to 15 dB for reliable communication.

The simulation settings are summarized in Table 1. In the next subsection, we evaluate the results.

B. EVALUATION OF MAXIMAL CLUSTER SIZE

To evaluate the performance of the proposed architecture, we first compute the maximal cluster size in the given settings and physical specifications of the data center. It must be noted that this is the upper bound of the cluster size. Due to a number of factors such as interference from other switches, wall penetration of the signals and signal path loss etc., the actual number of ToR switches per cluster or the cluster size may be different. As we assume that all the switches (transmitting and interfering) in our configuration of data center network is set same, the gains will not have much effect on the overall SINR. This means that if the gains of all switch antennas is set same, the maximal cluster size will not have a significant change.

In Fig. 4, the results for cluster size for different control traffic demands ranging from 0.1 Mbps to 1 Mbps with 5 GHz frequency setting and $30^\circ$ directional ToR switch antenna are given. As we have mentioned in the proposed architecture, it is recommended that the cluster should be square shaped. This will closely relate to our analytical calculations. In our simulations, we have compared the actual cluster size and the near-perfect square-shaped cluster size, which is shown in Fig. 4.

It is observed in Fig. 4 that the maximal cluster size under a demand of 0.1 Mbps is 148 ToR switches per cluster. If we convert this number to the closest perfect square cluster, then the cluster size is about 144 ToR switches per cluster. As the demand is increased to 1 Mbps, the perfect square shaped cluster size is reduced to 9, whereas the actual cluster size is about 15 ToR switches per cluster. These results are obtained when all the ToR switch antennas have a beam width of $30^\circ$ and operate at the 5 GHz frequency band. We do not consider the bandwidth of the AP for receiving data here.

Next, we evaluate the results when using different beam size of the ToR switch antenna under two different frequency settings. As the beam size of the ToR switch antenna is increased, the neighboring ToR switches may interfere with each other when transmitting simultaneously. Thus, the cluster size will reduce because the control traffic demands of the ToR switches cannot be satisfied.

In Fig. 5a, the results for maximal cluster size under different beam size of the ToR switch antenna when operating at 5 GHz frequency. It is observed in Fig. 5a that the cluster size under a beam width of $30^\circ$ for the ToR switch antenna using 5 GHz frequency band at 0.1 Mbps is about 148. Whereas for $60^\circ$ and $90^\circ$, the cluster size is reduced to 69 and 42 respectively. As the demand is increased to 1 Mbps, the cluster size is 15, 7, and 6 for $30^\circ$, $60^\circ$ and $90^\circ$ ToR switch antenna respectively.

We also simulate for ToR switch antenna with frequency settings of 2.4 GHz. The results are shown in Fig. 5b. It is observed from the results that the maximum cluster size at this setting is 86, using a ToR switch antenna with a beam width of 30 degree. As the beam width of a ToR switch antenna is increased to $60^\circ$ and $90^\circ$, the maximal cluster size is reduced to 38 and 22 for a demand of 0.1 Mbps. As the demand is increased to 1 Mbps, the maximal cluster size is reduced to 8 and 22 respectively for $30^\circ$, $60^\circ$ and $90^\circ$ ToR switch antenna respectively.

In comparison to 2.4 GHz frequency band, 5 GHz band yields higher maximal cluster size due to the fact that with higher operating frequency the supporting data rate increases. Considering the same control traffic demand and changing the frequency of transmission, 5 GHz band transmission will perform better compared to 2.4 GHz due to higher information carrying capacity.

Once the maximal cluster size is determined, the APs are placed at the center of these clusters by determining the centroid of the locations of the corner ToR switches. In the next subsection, we evaluate the maximal throughput between the ToR switches and the controller.

C. EVALUATION OF MAXIMUM THROUGHPUT

As our SDN architecture is purely wireless, the throughput is smaller when compared to a wired SDN. We evaluate the maximal cluster size will reduce. The reason is that when the beam size of the ToR switch antenna is increased, the neighboring ToR switches may interfere with each other when transmitting simultaneously. Thus, the cluster size will reduce because the control traffic demands of the ToR switches cannot be satisfied.

FIGURE 4. Comparison of perfect square cluster size and actual maximal cluster size with ToR switch antenna beamwidth of $30^\circ$ operating at 5 GHz frequency band for a traffic demand of 0.1 - 1 Mbps.
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maximum throughput (achieved between the ToR switches and the APs) for our data center network shown in Fig. 3. We select some configurations of the cluster sizes to derive a specific number of the APs (from 50 to 400 APs) at respectively 5 GHz and 2.4 GHz frequency. The configurations selected are rounded to nearest square size to match with our calculations.

The results for the maximal throughput achieved between the ToR switches and the controller are shown in Fig. 6. At 5 GHz, the maximal throughput achieved for 50 APs is 0.15 Mbps, whereas at 2.4 GHz, the throughput is reduced to 0.09 Mbps using a 30 degree ToR switch antenna. As the cluster size is reduced and the number of APs increase, the maximal throughput is 1.23 Mbps and 0.69 Mbps at 5 GHz and 2.4 GHz frequency respectively. It can be observed that with 50 APs, the demand of 0.1 Mbps can be met at 5 GHz, which is sufficient for the common amount of control traffic in data center networks. For higher control traffic demands (up to 1 Mbps), the number of APs is increased then the overall cost of wireless control plane deployment will increase and the solution may be infeasible. In the next subsection, we evaluate the result for the RN placement algorithm.

D. PLACEMENT OF RELAY NODES

In this subsection, we evaluate the effectiveness of our RN placement algorithm. The RNs can only be placed at the given candidate locations. In Algorithm 2, we select the minimal candidate locations to connect the APs with the controller. As an example, we select the case of 49 ToR switches per cluster (which gives us \( \frac{4900}{49} = 100 \) APs). The placement of the APs and the controller along with the candidate locations of RNs are shown in Fig. 7. The initial connectivity graph shown in Fig. 7 is based on the transmission range of RNs, shadowing and interference in wireless signals between RNs placed at these candidate locations. There are 16 APs that are within the transmission range of the controller and can easily connect with the controller without the help of a RN. The rest of the 84 APs need to be connected to the controller by placing RNs at candidate locations as computed by Algorithm 2.
After applying Algorithm 2 to the network in Fig. 7, we obtain a set of selected edge RNs that connect the APs to the controller, as it is shown in Fig. 8. A set of 15 candidate locations \( r_{10}, r_{8}, r_{21}, r_{28}, r_{29}, r_{9}, r_{14}, r_{26}, r_{6}, r_{35}, r_{36}, r_{12}, r_{15}, r_{23}, r_{31} \) (arranged in the order of their selection) are selected to place edge RNs.

Now, our algorithm selects additional candidate locations to connect these edge RNs to the controller as shown in Fig. 8. As the algorithm runs, first the furthest candidate node location from the Controller is selected. Candidate locations \( r_{6}, r_{9}, r_{35} \) and \( r_{36} \) are the furthest from the Controller, so node \( r_{6} \) is selected to build the first path. The first path \( r_{6} - r_{7} - r_{12} - C \) is selected. Later this path is joined by \( r_{8} - r_{9} \) through \( r_{12} \). Extra candidate sites are also selected through this algorithm to join the path. As this path can no longer satisfy the constraint in Eq. 12, other shortest paths are built the same way to connect remaining edge RNs.

It is observed from the results that in addition to 15 edge RNs, 6 extra candidate locations are selected to form the entire backbone tree. Out of the 37 candidate locations sites, the algorithm selects a total of 21 candidate sites to place the RNs in order to guarantee the connectivity and bandwidth constraint of the network.

Through these simulations, we observed that only a few number of APs and RNs are required to build a wireless control plane of 4900 ToR switches or racks in a SDN data center. The number of APs and RNs are feasible enough to cut the cabling complexity that would have been involved in a wired control plane compared to the proposed wireless control plane solution.

**VI. CONCLUSION**

In this paper, we proposed an end-to-end wireless control plane design for SDN-enabled data center networks. We propose an architecture in which switches form clusters and are connected to controller via access points (APs) and relay nodes (RN). In this architecture, all the nodes use directional antennas so that the required throughput can be achieved and interference is reduced. The switches use 2.4/5 GHz frequency band with TDMA to connect with the APs. Whereas the APs and the RNs use 60 GHz band with OFDMA and beamforming to connect with the controller. We proposed two algorithms. The first algorithm computes the maximal cluster size that satisfies the control traffic demand of the switches. After the maximal cluster size is determined, the APs are placed at the centers of these clusters. In the second algorithm, we determined the minimal number of RNs that connect all the APs that are out of the transmission range of the controller. Our algorithm places the minimal number of APs and RNs that can build a pure wireless control plane. The results show that only a few number of APs and RNs are required for building a pure wireless control plane in a data center network thus reducing the cabling complexity of a building an additional wired control plane in SDN data center. We conclude that it is feasible to deploy an end-to-end wireless control plane in a data center network using APs and RNs.

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