An Energy-Efficient, Wireless Top-of-Rack to Top-of-Rack Datacenter Network using 60GHz Links

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Abstract — Datacenters have become the digital backbone of the modern society and consume enormous amounts of power. Significant portion of the power consumption is due to the power hungry switching fabric necessary for communication in the datacenter. Additionally, the complex cabling in traditional datacenters pose design and maintenance challenges and increase the energy cost of the cooling infrastructure by obstructing the flow of chilled air. Recent research on wireless datacenters has proposed interconnecting rows of racks at the top-of-rack (ToR) level via wireless links to eliminate the need for complex network of power hungry routers and cables. Links are established using either highly directional phased array antennas or narrow-beam horned antennas between those ToR entities. ToR-to-ToR wireless links have also been used to augment existing wired networks, improving overall performance characteristics. All these wireless approaches advocate the use of 60GHz line-of-sight (LoS) communication paths between antennas for the establishment of reliable wireless channels. In this work, we explore the feasibility of a ToR-to-ToR wireless network for a small to medium-scale datacenter from the perspective of system-level performance. We evaluate a ToR-to-ToR wireless datacenter network (DCN) for network-level data rate and overall power consumption and compare it to a traditional fat-tree based DCN. We find that the ToR-to-ToR wireless DCN can sustain similar data rates for typical query based applications and consume less power compared to that of traditional datacenters.

Keywords— Wireless datacenter; Energy Efficiency; 60GHz; IEEE 802.11ad; Top-of-Rack;

I. INTRODUCTION

Datacenters have increasingly become the backbone of the modern digital world as they provide an illusion of infinite processing power and storage. One challenge is, however, the high energy consumption of datacenters. A census conducted by Natural Resources Defense Council (NRDC) shows that the energy consumption by datacenters reach 91 billion kWh energy in 2013, and will increase to 140 billion kWh by 2020 [1]. As the number of servers within a datacenter grows, the role of the interconnection infrastructure becomes paramount in terms of both energy efficiency and performance. Traditionally, datacenter networks (DCNs) have been interconnected in tree-based topologies using wired links and multiple hierarchical levels of aggregation. These tree-based networks and even recent alternative technologies exhibit inherent limitations in scalability and oversubscription as they rely on copper or optical cable based links [2].

The wired network technologies require power-hungry switching fabrics and create large bundles of wires, causing design and maintenance challenges and obstructions to the flow of chilled air for cooling [3]. Inefficient cooling resulting from networking and cabling complexities only exacerbates the energy efficiency problems that plague the current datacenters. To address these common design issues that wired or cabled datacenters face, we investigate wireless datacenter architectures as a promising alternative [4]. Recently proposed wireless DCNs leverage newly developed transceivers that utilize the unlicensed 60GHz radio frequency (RF) band. Advancements in the 60GHz technologies enable the transceivers to consume low power even in the milliwatt range [5][6]. These transceivers can establish multi-gigabit communication channels over distances of up to 10m [7]. Moreover, the 60GHz channels exhibit a certain degree of spatial reusability, allowing multiple concurrent links reusing frequency bands to be formed within the same datacenter. The small amount of power consumption combined with the ability to form multi-gigabit channels makes these transceivers ideal for use in wireless DCNs.

In this paper, we propose a wireless DCN architecture based on the 60GHz band that establishes direct single-hop links between the ToRs instead of tree topology, resulting in energy savings in data transfer. While the wireless network cannot provide the same physical cross sectional bandwidth afforded by wireline networks, we demonstrate that the wireless DCN is capable of supporting the same data rate as the conventional ones for typical textual query based applications common to datacenters [8]. We then estimate the power consumption of the proposed wireless DCN architecture and compare it to that of conventional counterparts in our case studies. To the best of our knowledge, this is the first attempt to measure the network-level characteristics of a TOR-to-TOR wireless DCN.

II. RELATED WORK

There are different approaches that have been proposed to address datacenter design issues such as energy consumption, cabling complexity, scalability, and over-subscription. The most common topology used today in datacenter networks is a fat-tree topology. In this topology, servers are connected through a hierarchy of access, aggregate and core layer...
switches. The core switches also serve as gateways to the external Internet. The datacenters utilizing this topology result in a problem of congestion or oversubscription at the upper levels of the hierarchy while the wired links cause maintenance challenges and obstruct the path of chilled air for cooling [2][9]. Several alternative DCN architectures such as BCube [10], DCell [11], DOS [12], VL2 [13], Helios [14] has been proposed previously. BCube is a recursive topology specially designed for shipping container based modular datacenters. DCell is also a recursively defined structure. DOS exploits wavelength routing characteristics of a switching fabric based on an Arrayed Waveguide Grating Router that allows contention resolution in the wavelength domain. VL2 uses Valiant Load Balancing to spread traffic uniformly across network paths. Helios is a hybrid electrical and optical switch architecture that can deliver significant reductions in the number of switching elements. However, these innovations still rely on copper or optical cables and do not eliminate the challenges due to a wired DCN with physical links.

To alleviate the issues of conventional DCNs with bundles of cables wireless datacenters with mm-wave inter-rack links are envisioned in [4][15][16][17]. Most of the recent works on wireless datacenters propose interconnecting entire racks of servers as units with 60GHz wireless links primarily in order to utilize the commodity Ethernet switching between servers inside individual racks [4]. Phased antenna arrays or directional horn antennas are used to establish wireless links between Top-of-Racks (ToRs) in the entire datacenter [17][18]. Line-of-Sight (LoS) communication paths are necessary between the antennas for reliable communication in a wireless datacenter [17]. Paths through metal frames and racks will have increased losses due to obstructions. Hence, reflectors on ceilings and walls in the form of metallic mirrors or signal relays can be mounted to form paths where direct LoS does not exist [19]. In [20] a cylindrical arrangement of servers is proposed to create LoS wireless links between servers. This however, requires non-traditional cylindrical arrangement of servers having implications on cooling, server density and scalability of the DCN which are not well known at this point.

Owing to its capability to deliver very high communication rates, the unlicensed 60GHz wireless band has been the subject of attention for a number of years [21][22][23][24]. These efforts have led to the development and approval of the IEEE 802.11ad wireless local area network (WLAN) standard in December of 2012 [25][26]. This standard extends the IEEE 802.11 family of WLAN standards to enable networking in the 60GHz unlicensed spectrum band within the V-Band frequencies in the US and achieving data rates of up to almost 7Gbps over distances of up to 10m [27]. A number of works have followed the approval of the standard with the design of the corresponding transceivers [7][28][29]. These recent developments make using 60GHz wireless links suitable for wireless DCNs. In this paper, we evaluate a ToR-to-ToR 60GHz wireless DCN and establish its feasibility from the perspective of system-level performance evaluation.

III. WIRELESS DATACENTER NETWORK ARCHITECTURE

In this section, we discuss the architecture of the ToR-to-ToR wireless DCN. We describe the design methodologies for the architecture, then the antenna technology adopted, and finally its communication protocols.

A. Wireless Datacenter Network Topology

In the proposed datacenter network, the ToR switches establish links with other racks via completely wireless interconnections over 60GHz bands. Servers within a rack are connected through traditional wired links (e.g., Ethernet) to the ToR switches. A ToR wireless module in each ToR switch contains a transceiver and antenna capable of communicating with another ToR wireless module. This ensures direct single-hop communication between any pair of ToRs to simplify the routing and link establishment mechanisms. As illustrated in Fig. 1, datacenter racks are laid out in traditional configurations, with aisles running between rectangular rows of datacenter racks. The wireless transceiver and antenna module sit atop each of the racks. Each ToR module is assigned an ID, and we assume that the spatial location of all ToR modules and their orientations are known.

The completely wireless ToR level in datacenter networks is justified as a viable solution for the following reasons:

- The 60GHz wireless links can sustain comparable data rates to those of wired datacenter networks [15]. Typical link speed between the ToR and the aggregation level in today’s datacenter are around 1Gbps, with faster datacenters using links at 10Gbps to connect the ToR level [30]. The 60GHz wireless links are capable of sustaining 6.76Gbps per subcarrier as discussed later in section IIIIC. Moreover, the single-hop communication available in the wireless datacenter reduces routing complexity and data transfer latency significantly.

- The completely wireless ToR level alleviates the cabling complexity problem, as the inter-rack, aggregation, and core level connections and cables are eliminated. This reduction also allows more space above and between racks, freeing up critical line-of-sight paths needed for reliable wireless communication.

Figure 1. Wireless Data Center with wireless ToR routers.
• The wireless ToR level also reduces the number of levels of aggregation and removes many power-hungry switches at the core and aggregation-levels. This allows two racks to communicate with other racks simultaneously, and hence mitigates contention and oversubscription at aggregation or core-level switches. As a result, the network becomes more power-efficient and less congested.

Despite these advantages and feasibility of the 60GHz wireless links, in this DCN we still use wired technologies for intra-rack server connections (e.g., between blade-type servers) mainly for practical reasons. For example, we can utilize the common power and cooling resources that are already installed. Additionally, large metal rack frames form an obstacle for wireless antennas at the server level to establish one-hop links to a ToR module. The connectivity to the external internet will be provided via designated ToR level switches chosen to provide the required external bandwidth and functionality.

B. Antenna Technology for the Wireless Datacenter

Each ToR is equipped with a 60GHz wireless module to enable the wireless DCN. Inside each of the ToR wireless modules, there is a transceiver and an accompanying horn antenna. While on-chip antennas are compact and phased arrays provide electronic beam-steering capabilities, such antennas within the 60GHz band are still an emerging technology. In contrast, a horn antenna is widely available with proven capabilities even at 60GHz [15][30]. Also, horn antennas can provide directionality to each of the wireless modules and connect distant racks within the datacenter at multi-gigabit data rates. Therefore, the use of mechanically steered horn antennas is proposed [15] and adopted in our work. The mechanical steering of the antennas to face each other has a timing response of under a second [15]. This orientation of the receiving antenna is achieved by using a separate control band using standard 2.4/5 GHz WiFi bands. Each ToR is equipped with a separate peer-to-peer WiFi broadcast transceiver. The ToR ready to send data sends a short control message to receiving ToR simultaneously with orienting its transmitting horn antenna towards the receiver. Upon receiving this control message the receiver wireless module orients its horn antenna towards the sending ToR. Then the data transmission is achieved over the horn antennas. The antennas operate in conjunction with the transceiver modules at a bit error rate (BER) of 3x10⁻⁷. This BER is a function of the signal to interference plus noise ratio (SINR) and the 802.11ad protocol corresponding to the data rates sustained by the wireless links. Next, we discuss the adopted wireless protocol suitable for the wireless DCN.

C. Wireless Communication Protocols

Establishing connections between ToR modules requires reliable wireless 60GHz physical and MAC layer protocols. The IEEE 802.11ad standard is designed for 60GHz wireless LANs at and beyond a distance of 10 meters. This standard defines a physical layer protocol that supports beam-forming, and also supports extremely high data rates in both a single channel (SC) and Orthogonal Frequency Division Multiplexing (OFDM) mode of operation. The maximum achievable data rate is 4.62Gbps for the SC and 6.76Gbps for the OFDM mode. For these high data rates and transmission distances above 10 meters, we adopt the IEEE 802.11ad standard as the 60 GHz physical layer protocol for wireless datacenters [15].

We use the 802.11ad MAC layer protocol that incorporates a Carrier Sensing Multiple Access (CSMA) mechanism for on-demand establishment of wireless links depending upon the traffic flow requirements that, in turn, depend on datacenter tasks. After the control request is exchanged over the 2.4/5GHz WiFi band and after the receiving ToR orients its antenna towards the sender, a link is established if permissible by the CSMA scheme supported by the IEEE 802.11ad standard. This MAC layer establishes as many non-interfering links as possible greedily on a first-come first-serve basis until all traffic flow demands are met or all the available OFDM channels are exhausted. Once a link is found to be infeasible due to interference with already-existing links, the link is no longer considered and that demand is left incomplete. While this greedy on-demand MAC protocol may not reach an optimal state, it effectively achieves a near-optimal solution with negligible computational overhead. Due to the adopted CSMA MAC mechanism described here, only a single communication flow can be established from any ToR using the wireless module at any given time provided, the interference is acceptable according to the IEEE802.11ad standard. Therefore, each ToR can communicate with only one other ToR at the same time. We evaluate the performance of the MAC layer protocol through a comparison and analysis against similar-sized wired networks in our case studies. We adopt TCP as the transport layer protocol for reliable packet delivery for its widespread use and well-known characteristics in datacenter networks [15]. In the following section, we evaluate the ToR-to-ToR wireless DCN through some case studies.

IV. CASE STUDIES AND ANALYSIS

An experimental or simulation based analysis of a completely wireless ToR-to-ToR DCN from a system level perspective has not been done previously. Therefore, in this paper, we establish the feasibility of a completely wireless ToR-to-ToR DCN and demonstrate with network-level simulations that it can sustain comparable performance to that of conventional DCNs. In our analysis, we have only considered the performance of the DCN between racks within a datacenter and have not captured server-level characteristics or interactions with the external internet. After establishing the performance, we estimate the power consumption of the proposed wireless DCN and compare it with traditional cabled DCNs.

A. The Simulation Platform

We use the NS3 network simulator [31] that allows evaluating both wired and wireless networks under the same conditions, and supports the characteristics of wireless
propagation as well as network-level communications. It is important to simulate both the propagation and network-level communication characteristics accurately in order to obtain credible performance results. More specifically, we use a modified version of NS3 that is extended with wireless datacenter features including 60GHz links and the IEEE 802.11ad standard as discussed in [15]. The extension incorporates interference modeling, bit error rates, and directional antenna modeling, and the accuracy of which is verified with physical layer measurements from their prototype 60GHz hardware. The topology of the DCNs studied here are set up in NS3 capturing the geometry of the arrangements to accurately model interference among the wireless links. Additionally, we introduce criteria for wireless link selection to enable many concurrent links, and modify the 802.11ad OFDM physical layer channel to allow multiple channels operating at gigabit speeds in the simulator.

B. Traffic Generation

In the experiments, we generate traffic flows following application demands representative of the aggregate traffic requirements of all servers within a rack, as the network being studied is at the ToR-to-ToR level. To evaluate the performance of wireless links between ToRs, practically measured data from real datacenters, consisting of different applications like map-reduce and index lookup has been used previously [15] with their flow sizes and arrival rates verified in [16]. We use the same traffic pattern in our paper. The traffic flows include information specifying start time, source, destination, volume, and data rate at which traffic is generated. We use a set of 1,000 traffic flows generated over 100 seconds, with random data sizes between 1MB and 1GB and uniform random data rates between 10Mbps and 1Gbps. The data sizes reflect the volume of ToR traffic and the data rates reflect the rate applications produce traffic within a rack. We set the MTU (Maximum Transmission Unit) to 10KB as most datacenter traffic flows are less than that [8]. Such traffic is common in applications such as Map-reduce, which is typically encountered in textual query based tasks, common in datacenters [8]. Additionally, the wireless environment is relatively stable as each transceiver remains fixed spatially, reducing the number of bit errors and subsequently the need for retransmission. This combination of high data rates and stable environment allows for a higher MTU to be advantageous in wireless transmissions. This generated traffic was then injected into the DCNs using the modified NS3 platform described in section IVA earlier to evaluate their performance.

C. Wireless DCN Performance

We evaluate the DCNs with respect to the number of completed traffic flows, link throughput, and power consumption. The number of completed traffic flows denotes the number of application demands that are completed over a given time frame. Several parameters affect the number of completed traffic including network type, the amount of oversubscription present, and the speed of network links.

In our experiment, 10 racks are arranged in a single row with two columns of eight rows, totaling 160 racks or ToRs. Each rack is 1 meter by 1 meter wide and 2 meters tall. There are 2 meters of spacing between rows within a column, and 3 meters of spacing between columns. The geometry is representative of a typical datacenter room for a medium size datacenter, typically found in educational institutions or private enterprises according to the Data Center Institute’s Data Center Size and Density Standard [32]. Each ToR is equipped with a wireless transceiver and a directional horn antenna.

In addition, two wired Three-Tier DCNs are evaluated for comparison with the wireless DCN using the same traffic flows over 100 seconds. One wired network consists of 1Gbps links between the ToR access-level switches and the aggregation switches, and 10Gbps links between the aggregation and core switches. This wired network is identified as the 1/10 wired network (referred to as 1/10). The wired network represents a conventional datacenter using standard commercial equipment and link speeds. The 1/10 wired network consists of 160 access switches, two aggregation switches, and two core switches. This network has an oversubscription ratio of 4:1 with 160Gbps of downstream aggregate bandwidth and 40Gbps of aggregate upstream bandwidth. The second wired network called the 10/40 wired network (referred to as 10/40) also follows the
same Three Tier configuration with the only difference being in the link bandwidths. 10Gbps links between the ToR access and the aggregation switches and 40Gbps links between the aggregation and core switches are used. With these higher link speeds, the 10/40 wired DCN represents a high-end datacenter. The 10/40 wired network consists of the same number of switches as 1/10, with an oversubscription ratio of 10:1 with 1600Gbps of downstream aggregate bandwidth and 160Gbps of aggregate upstream bandwidth.

The wireless DCN is first evaluated with a single 60GHz channel, the 802.11ad PHY and MAC layers, and the corresponding SC rates. All 160 ToR wireless modules are connected to their respective access switches initially in the idle mode of operation. Whenever a traffic flow finishes, the wireless transmitters cease communication and return to the idle states. The same experiment is repeated for both 4 and 12 channels while they use the faster 802.11ad OFDM rates instead of the SC rates. All the experiments are run over 100 seconds with 1,000 traffic flows. The overheads of the WiFi control messages and antenna steering are not considered in this work. However, as long as the data communication is bursty with large payloads as is common in www environments, the proportion of control messages will be negligibly low.

Fig. 2 shows the number of completed demands for the different DCNs. The 1/10 and 10/40 DCNs complete a maximum of 838 flows and 860 flows, respectively, whereas the SC wireless DCN completes a maximum of 211 demands. This is significantly lower as the number of non-interfering concurrent wireless links that could be established is approximately one fourth of the number of links utilized in the wired networks. The 4-channel wireless DCN that can support 6.67Gbps data rates completes 732 demands over 100 seconds. While this is better than the SC Wireless DCN, the number of completed flows is still lower than the 1/10 DCN.

We observe that there are links that cannot be established due to interference with other links even with 4 separate channels. Worse, each of the channels support a larger data rate, i.e., 6.67Gbps, than the rates demanded by the application, which are only up to a maximum of 1Gbps. Therefore, we expect further subdividing the channels might improve the bandwidth utilization per channel. As expected, the 12-channel wireless DCN completes more flows, which is 854 demands, which is higher than that of the 1/10 DCN and nearly as many as the 10/40 DCN.

Fig. 3 shows the throughputs of the completed application demands for the wired and wireless DCNs. The results show that the wireless DCNs can surpass the conventional 1/10 wired network, and even achieve throughput comparable to that of the high-end 10/40 wired DCN. We also observe a trade-off between the number of completed demands and throughput. Although SC maintains the highest throughput, the number of completed links is the lowest; 12-channel satisfies a large number of demands, but cannot sustain as high of throughput as the other wireless DCNs. This is because in the SC wireless DCN the bandwidth of the wireless channel is the highest and some traffic demands with high bandwidths can only be sustained with those wireless links. These high data rate traffic demands could not be sustained at their desired rates in the OFDM wireless DCNs resulting in performance degradation. The data rates being slower in the 12-channel DCN compared to the 4-channel case, the performance degradation is larger in the latter. However, in the type of applications, we have considered here, such high data rate applications are few in number and hence, their impact is not severe. Therefore, even the 12-channel wireless DCN is able to provide better throughput compared to the 1/10 DCN due to direct single-hop links between ToRs. Next, we estimate the power consumption of a wireless DCN and compare it to the conventional DCNs.
D. Power Consumption

It is challenging to establish an accurate power consumption model for the entire power portfolio of a given datacenter. The server and rack power consumptions largely depend on the efficiency and number of underlying computational components. Moreover, the cooling and ventilation costs are influenced by the geographic location, the efficiency of the building layout, and the reliability level of the datacenter. As the primary focus of this work is the datacenter network, only the power consumption of the network components is modeled and evaluated. Our architecture leverages its power consumption improvements from the removal of the core and aggregation switches and collapsing the tree-based wired network into wireless one-hop links. In other words, small wireless transceivers take the place of those switches at a fraction of the power consumption. The power consumption of the wired DCNs is the sum of all the powers consumed at each network layer. This total power consumption of the entire DCN is:

\[ P_{Total} = Num_{core}P_{core} + Num_{agg}P_{agg} + Num_{acc}P_{acc} \]  

(1)

Where \( Num_{core}, Num_{agg}, Num_{acc} \) are the number of core, aggregation, and access switches, respectively, and \( P_{core}, P_{agg}, P_{acc} \) are the power consumptions of an individual core, aggregation, and access switch, respectively. We consider ThreeTier wired DCNs comprising the access, aggregation and core layers, and Cisco Nexus Platforms to represent the switch power consumptions of the ThreeTier DCNs \[33][34][35]. A survey of developing 60GHz wireless transceiver technologies illustrates that these transceivers consume only hundreds of milliwatts to operate at gigabit data rates \[5].

We use estimates of power consumption for the wireless module including the 2.4GHz WiFi control module conservatively, i.e., 1W for the maximum and 500mW for the typical and communicating module. Not many transceivers communicate actively at any given point in time, making the use of 500mW for every module a worst-case scenario in which all wireless modules are active. Furthermore, as the 60GHz-related technologies mature, the transceivers operating at these frequencies will become more power-efficient. When estimating the power consumption of wireless DCNs with multiple channels, the transceiver power consumption is multiplied by the number of channels to represent a worst-case scaling in power. While the antennas being passive elements do not consume any power, the antenna positioners consume around 1W each, which is considered in our power consumption model. The power consumption of the individual components in the conventional and wireless DCNs that are considered to estimate the total power are shown in Table 1.

The power consumption for all simulated networks is shown in Fig. 4. The power consumptions are estimated using the values in Table 1 and equation (1). The results show that the wireless DCNs use 6-8\% less power than wired networks at the maximum, and 13-16\% less power in the typical power consumption. While the majority of power is used at the ToR access-level switches, these switches cannot be removed from the wireless DCNs because the intra-rack Network Interface Cards (NICs) still employ wired links to reach the ToR switch. The power gains mainly come from eliminating the aggregation and core level switches. Note also that a large gap exists between the maximum and typical consumptions as the maximum consumption occurs when the network components are used at their highest power levels. Although this peak network utilization rarely occurs in practice, datacenters should be able to support this maximum level to ensure robustness. The wireless DCN demonstrates that it can reduce the maximum power consumption considerably. Of course, as ToR access network switches become more power efficient, the wireless DCN also realize those energy savings. As shown in the figure, all wireless DCNs (SC, 4-channel, and 12-channel) save energy compared to the wired DCNs (10/40 and 1/10).

V. Conclusions and Future Work

In this work, a fully ToR-to-ToR wireless DCN architecture is proposed. The 12-channel wireless DCN is able to outperform the 1/10 wired network in terms of the number of completed traffic flows and in terms of the achievable average throughput. Furthermore, the 12-channel wireless DCN demonstrates a 7\% lower average maximum power consumption and a 15\% lower typical power consumption when compared to the wired DCNs. In summary, the wireless DCN architecture is proven to be feasible as an alternative datacenter network with advantages in performance and power consumption.

Wireless DCNs alleviate many modern networking challenges, however, they are not without their own set of challenges such as scaling up the size of the datacenter and completing dropped traffic flows due to interference. Further research and investigation is necessary to solve these additional challenges. Moreover, due to the introduction of wireless communication the security and privacy of the data may potentially be compromised. Security and privacy in wireless communications are customarily addressed through the use of authentication and encryption. The overheads on
power and performance of the wireless DCN due to incorporating authentication and encryption needs to be investigated. Nevertheless, wireless 60 GHz DCNs show great promise in replacing burdensome cabling issues and project significant power savings at a comparable performance to that of conventional counterparts. This work provides a network level case study of one type of wireless datacenter architecture. The wireless DCN architecture proposed in this work can provide a foundation for numerous future works.

ACKNOWLEDGMENT

The authors would like to thank Dr. Andres Kwasinski, Rochester Institute of Technology and Mr. Avery Francois, former student at Rochester Institute of Technology for their valuable contributions towards improving this work.

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