Wireless 60 GHz Rack to Rack Communication in a Data Center Environment

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Wireless 60 GHz Rack to Rack Communication in a Data Center Environment

by

Avery John Francois

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science in Computer Engineering

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I would like to dedicate this thesis to my family and loved ones who have supported me throughout my academic endeavors.
I would like to acknowledge my thesis advisor, Dr. Amlan Ganguly for guiding me throughout my thesis. I would also like to acknowledge Dr. Minseok Kwon and Dr. Andres Kwasinski for serving on my thesis committee and providing their support.
Abstract

Wireless 60 GHz Rack to Rack Communication in a Data Center Environment

Data centers play an increasingly important role in processing the large amount of information generated in today's society. An enormous amount of growth in the computational demands of data center applications has stimulated the creation of warehouse scale data centers, holding servers that number in the thousands. As the number of servers within a data center grows, the interconnecting infrastructure becomes of paramount importance. Present day interconnects are formed using either copper wire in a twisted pair configuration or through the use of fiber optic cables. One of the main concerns with the scalability of a data center's interconnecting network is the power consumption. Large power hungry switches at the aggregation and core levels make up a significant portion of a data centers power portfolio and cannot be overlooked. Furthermore, large bundles of wires both reduce the air flow within data centers and are costly to replace and maintain. This cabling complexity problem limits cooling effectiveness and exacerbates the power consumption challenges.

Recent advancements in the unlicensed 60 GHz spectrum have given rise to transceivers that can support high bandwidth links, comparable to wired links found in most data centers. These wireless links also exhibit promising characteristics such as spatial reusability which make them suitable within a data center environment. By taking advantage of emerging 60 GHz wireless technologies, data centers can utilize these high speed wireless links to satisfy bandwidth demands while simultaneously reducing their power consumption and cabling requirements.

This thesis evaluates the benefits in terms of energy-efficiency of using 60 GHz wireless links to replace wire line links within a data center by modeling a completely wireless data center. The physical layer design and associated MAC layer will be investigated to support this wireless centric design. The proposed wireless architecture will be compared against traditional hierarchical data center architectures and evaluated based upon several performance metrics such as throughput, latency, and overall energy efficiency.
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<th>Abbreviation</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>DCN</td>
<td>Data Center Network</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>ToR</td>
<td>Top of Rack</td>
</tr>
<tr>
<td>LoS</td>
<td>Line of Sight</td>
</tr>
<tr>
<td>MAC</td>
<td>Medium Access Control</td>
</tr>
<tr>
<td>FCC</td>
<td>Federal Communications Commission</td>
</tr>
<tr>
<td>ETSI</td>
<td>European Telecommunications Standards Institute</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronic Engineers</td>
</tr>
<tr>
<td>WPAN</td>
<td>Wireless Personal Area Network</td>
</tr>
<tr>
<td>WLAN</td>
<td>Wireless Local Area Network</td>
</tr>
<tr>
<td>UHF</td>
<td>Ultra-High Frequencies</td>
</tr>
<tr>
<td>dB</td>
<td>Decibels</td>
</tr>
<tr>
<td>dBi</td>
<td>Decibels Equivalent Isotropic Radiated Power, 1 Watt reference</td>
</tr>
<tr>
<td>dBmi</td>
<td>Decibels Equivalent Isotropic Radiated Power, 1 Milliwatt reference</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
</tr>
<tr>
<td>OOK</td>
<td>On Off Keying</td>
</tr>
<tr>
<td>BPSK</td>
<td>Binary Phase-Shift Keying</td>
</tr>
<tr>
<td>QPSK</td>
<td>Quadrature Phase-Shift Keying</td>
</tr>
<tr>
<td>OFDM</td>
<td>Orthogonal Frequency Division Multiplexing</td>
</tr>
<tr>
<td>SC</td>
<td>Single Channel</td>
</tr>
<tr>
<td>MCS</td>
<td>Modulation and Coding Scheme</td>
</tr>
<tr>
<td>NS-3</td>
<td>Network Simulator 3</td>
</tr>
<tr>
<td>RSS</td>
<td>Received Signal Strength</td>
</tr>
<tr>
<td>SINR</td>
<td>Signal to Interference plus Noise Ratio</td>
</tr>
<tr>
<td>BER</td>
<td>Bit Error Rate</td>
</tr>
<tr>
<td>TCP</td>
<td>Transmission Control Protocol</td>
</tr>
<tr>
<td>MTU</td>
<td>Maximum Transmission Unit</td>
</tr>
<tr>
<td>MIMO</td>
<td>Multiple Input Multiple Output</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

Numerous efforts in the form of academic research, conferences as well industrial progress have solidified the use of datacenters as the backbone of the modern digital world. According to a census by the Natural Resources Defense Council (NRDC) in 2013, data centers consumed 91 billion kWh of energy, and are expected to consume 140 billion kWh by 2020 [1]. As the number of servers within a data center grows, the interconnecting infrastructure becomes of paramount importance. Commodity data center networks (DCNs) have been traditionally interconnected in tree-based topologies using wired links and multiple hierarchical levels of aggregation. Alternate wired network topologies have been developed to solve inherent limitations in the scalability and oversubscription of tree-based designs, however these network topologies continue to rely on copper and optical interconnections [2]. These wired technologies require power hungry switching fabrics and necessitate the creation of large bundles of wires, causing maintenance challenges and obstructions to the flow of chilled air for cooling [3]. Inefficient data center cooling, resulting from networking and cabling complexities, exacerbates the energy efficiency problems that plague present-day data centers. Wireless data center architectures have emerged as promising alternatives to address the common design issues that wired data centers face [4].

Wireless DCNs leverage newly developed transceivers based upon the unlicensed 60 GHz radio frequency (RF) band. Advancements in the development of 60 GHz technologies have produced transceivers that consume power in the milliwatts range [5] [6]. These transceivers have the capability of establishing multi-gigabit communication channels over distances of up to 10m [7]. Moreover, these 60 GHz channels exhibit a certain degree of spatial reusability, allowing concurrent links to be formed within the same geographic location. The small amount of power consumption modern 60 GHz transceivers consume,
combined with their ability to form multi-gigabit channels, makes these transceivers ideal for use in wireless DCN designs.

Recent wireless data center works have proposed interconnecting entire racks of servers at the top of rack (ToR) level to utilize short distance wired links between servers within a rack [8]. Highly directional phased array antennas or narrow-beam horned antennas are used to establish links between these ToR entities. ToR wireless links have been used to augment existing wired networks, providing better overall performance characteristics [9]. On the other hand, several wireless data center works have abandoned traditional data center layouts in favor of novel geographic arrangements of racks to facilitate the creation of multiple wireless links [10]. In each wireless approach, the use of 60 GHz line-of-sight (LoS) communication paths between antennas are crucial to the establishment of reliable wireless channels.

Previous research concerning wireless DCNs provides the foundation from which this work builds upon. This work will draw upon several wireless data center concepts to demonstrate the proposed wireless DCN architecture. Additionally, this work will establish the feasibility of the designed wireless network and show that this fully wireless approach is capable of satisfying data center application demands. This work will then highlight the significant power consumption savings the wireless DCN architecture affords when compared to its wired counterpart.

1.1. Motivation

Research concerning data center design and efficiency has become more prevalent in both industry and academia due to the increasing reliance on data centers to manage complex services. With the advent of cloud computing, data center resources are scaling rapidly and will require new and innovative solutions to meet that demand. Several factors however, limit the scalability and efficiency of modern data centers and have proved challenging to overcome. The growing power consumption of modern data centers must be addressed in order to reduce their footprint and decrease costs. Large bundles of cabling necessary to interconnect medium and large scale data centers pose a significant maintenance challenge
and also block the flow of chilled air for cooling. Finally, the significant amount of aggregation performed in the core and aggregation levels of modern data centers contributes towards congestion and oversubscription problems. New data center network architectures must contend with each of these challenges in order to demonstrate their advantages over existing networks. These data center network challenges provide the motivation for this work and serve as the reason new network designs are necessary.

1.2. Thesis Contributions

This work seeks to evaluate the feasibility of a completely wireless data center using 60 GHz wireless links, and to compare its performance to several traditional hierarchical wired data center models. The scalability of DCNs poses significant challenges in terms of power consumption. Conventional DCNs are arranged in a tree based topology, bringing about significant congestion and oversubscription along wired links as the number of aggregation levels increase. Several solutions have emerged in an attempt to limit the amount of resources used to construct large DCNs, including server centric wired approaches and the use of 60 GHz links. These approaches will be explored and explained in depth in the background and related work section.

Many contemporary works studying wireless data centers using 60 GHz links have proposed using these links to supplement existing wired networks in a hybrid style approach. This proposed work attempts to replace a data center's inter-rack wired links entirely with wireless links. This will both maximize the energy savings obtained using wireless technology, while maintaining or improving the bandwidth provided by these wireless links in comparison to a wired network. In addition to the evaluation of an entirely wireless data center, this work will improve upon existing 60 GHz medium access control (MAC) mechanisms to further the wireless data center approach. A primary objective of this proposed work is to demonstrate that a completely wireless data center has the capability to satisfy bandwidth demands of a typical data center while yielding significant energy savings. Furthermore, this work will provide a foundation for future wireless data center investigations using 60 GHz links.
1.3. Thesis Layout

The layout of this thesis document is as follows: Chapter 2 will be devoted to the background and related works. This section will begin with an explanation of the motivational influences affecting DCNs and then move into an overview of all background information. This section will be broken into pieces, starting with an explanation of the existing wired and wireless data center approaches and will then transition into relevant 60 GHz background material. Chapter 3 will introduce the proposed wireless DCN architecture. This chapter will explain the topology, the method of link selection, the 60 GHz hardware employed, and network protocols used. A presentation of the results and an in depth analysis follows in Chapter 4. The simulation results are broken up into a logical progression, leading up to the proposed approach. Chapter 5 will finish with concluding remarks and will highlight the main problems addressed. This section will also include a brief outline of future works.
Chapter 2

Background & Related Work

This section will begin with the central problems afflicting modern data center designs and will provide substantial motivation for new network designs. All background and related work will then be introduced and discussed. This section will conclude with the significance this work provides.

2.1. Data Center Network Challenges

Several issues limit the performance and scalability of DCN designs. Three main network challenges are introduced and discussed in this section. These problems include the growing power consumption of DCNs, the increasing cabling complexities with large wired networks, and the traffic congestion observed in multiple layers of aggregation. Each of these challenges must be addressed to justify the feasibility of any modern network design.

2.1.1 Power Consumption

Data centers around the globe consume an enormous amount of electricity. When considered as a whole, they make up a significant portion of overall worldwide electricity usage [11]. The usage statistics for the world and the US are shown in Table 1.

<table>
<thead>
<tr>
<th>Location</th>
<th>Year</th>
<th>Communication Infrastructure Electricity Usage (billion KWh)</th>
<th>Total Data Center Electricity Usage (billion KWh)</th>
<th>Total Data Center Electricity Usage (% of total worldwide electricity usage)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Worldwide</td>
<td>2000</td>
<td>3.8</td>
<td>70.8</td>
<td>0.53%</td>
</tr>
<tr>
<td>US</td>
<td>2000</td>
<td>1.4</td>
<td>28.2</td>
<td>0.82%</td>
</tr>
<tr>
<td>Worldwide</td>
<td>2005</td>
<td>7.3</td>
<td>152.5</td>
<td>0.97%</td>
</tr>
<tr>
<td>US</td>
<td>2005</td>
<td>2.7</td>
<td>56</td>
<td>1.53%</td>
</tr>
<tr>
<td>Worldwide</td>
<td>2010</td>
<td>15.6</td>
<td>271.8</td>
<td>1.50%</td>
</tr>
<tr>
<td>US</td>
<td>2010</td>
<td>4.9</td>
<td>85.6</td>
<td>2.20%</td>
</tr>
</tbody>
</table>

Table 1: Electricity Usage within Data Centers [11]
Furthermore, the authors in [11] indicate that networking equipment already accounts for around 15% of a data centers infrastructure energy budget. This percentage is expected to increase in the future and is projected to grow by up to 50% in the coming years. Due to the fact that servers and cooling equipment represent the majority of a data centers electricity usage, they have received more research and attention [11]. While new technologies make cooling equipment and servers more energy efficient within a data center, the networking infrastructure must receive an equal amount of attention to prevent its energy consumption from growing unchecked. The energy efficiency problems associated with data centers are reinforced by a recent change in focus from the initial capital costs of setting up a new data center, to the cost in electricity of maintaining new data centers. The growth in data center infrastructure has driven down the cost of the initial equipment, however the cost of electricity recurs and adds up over time. The cost of powering a data center can quickly surpass the initial data centers total equipment cost.

2.1.2 Cabling Complexity

A major source of a data center's power consumption comes from the cost of cooling down the equipment within a data center. Inefficient cooling, resulting from networking and cabling complexities, only exacerbates energy efficiency problems [3]. While structured cabling and raised floor techniques mitigate the cabling complexity challenge, these cables still result in airflow blockage which leads to inefficient cooling [12]. The large bundles of cables and the complexity of cabling can be seen in Figure 1.
Even with structured cabling approaches, these wires hinder the ability of chilled air to move around the data center. These cabling overheads result in airflow blockages, additional maintenance costs, and can cost a great deal as a data center scales out. The physical cables within a data center represent a significant portion of the initial data center infrastructure costs.

### 2.1.3 Traffic Congestion

In addition to the power consumption and cabling problems, another important issue facing data centers is the congestion in traffic as links become aggregated. It is estimated that roughly 70% of data center traffic will flow within a data center between servers, placing a large demand on the structure of a data center’s internal network [13]. As the number of servers scales up into the thousands, it becomes impractical and costly to provide full link bandwidth from all servers to every other server. This has given rise to popular tree based topologies where links become aggregated to a switch and then further aggregated as necessary using additional switching levels. Various tree based topologies with two and three levels of aggregation have emerged to facilitate scaling of the number of servers in a data center. Two popular networks known as FatTree and ThreeTier are shown below.
When links become aggregated, the amount of bandwidth on upstream links is often less than the bandwidth of the downstream links. This difference in bandwidth leads to a concept known as oversubscription. Oversubscription is defined as the ratio of maximal aggregate bandwidth among end hosts in the worst case to the total bisection bandwidth [14]. Oversubscription saves network resources at the expense of possible contention for access to those network resources. As the amount of oversubscription increases, the impact to performance is an undesirable consequence and poses a potential problem if left unaddressed.
2.2. Related Work

This Wireless DCN work encompasses a number of recent advances in both data center design and in wireless technologies. This section begins with an overview of various data center network architectures and shows how the wireless DCN methodology fits in to the field of DCN research. A section on wireless DCNs will follow, with alternative network designs and other proposed wireless works. This section will then cover related background material on the 60 GHz frequency band, existing 60 GHz standards, channel characteristics, antenna technologies, and the spatial reuse of 60 GHz signals.

2.2.1 Data Center Networks

Many approaches have been proposed to address data center design issues such as energy consumption, cabling complexity, scalability, and oversubscription. The authors in [2] classify data center networking architectures into four categories, electronic switching technologies, all optical switching, hybrid optical and electronic switching, and wireless data center technologies. Each of these research categories seeks to improve the underlying networking architecture to solve various network challenges outlined in Table 2 [2].

<table>
<thead>
<tr>
<th>Name</th>
<th>Networking architecture</th>
<th>Switching granularity</th>
<th>Scalability</th>
<th>Energy Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fat-Tree</td>
<td>Electronic</td>
<td>Fine</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>BCube</td>
<td>Electronic</td>
<td>Fine</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>DCell</td>
<td>Electronic</td>
<td>Fine</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>VL2</td>
<td>Electronic</td>
<td>Fine</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>HyPaC</td>
<td>Hybrid</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>Helios</td>
<td>Hybrid</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>DOS</td>
<td>Optical</td>
<td>Coarse</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Scheme in [16]</td>
<td>Optical</td>
<td>Coarse</td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>

Table 2: A comparison of DCN architectures [2]

The electronic networking architectures rely on copper cables, predominantly twisted pair cables, which accounts for their high energy consumption and low scalability. The optical networking architectures use fiber optic cables as the backbone of the data center network, increasing the scalability and lowering the energy consumption at the cost of switching...
granularity. The hybrid architectures in this instance rely on a combination of both fiber optic and copper cables. The wireless network approaches in [9] and [15] keep the switching advantages offered by wired networks and employ wireless technologies on top of existing wired approaches. This provides several solutions to unbalanced bursty traffic and oversubscription issues, however these approaches still maintain a large energy consumption due to the underlying wired network. Addressing the energy consumption of wireless DCNs is necessary to allow these networks to compete with emerging alternative network architectures.

### 2.2.2 Wireless Data Centers

Recent works concerning wireless data centers specifically can be broken down into two distinct approaches [4]. The first approach is to augmenting existing wired networks to provide supplemental bandwidth to alleviate highly congested "hot-spots" [9]. Architectures such as [9] have proposed interconnecting entire racks of servers at the top of rack (ToR) level with wireless links between the tops of towers. The second approach is to create a fully wireless data center by either replacing wired links, or by creating a completely novel data center topology [18] [10]. Both approaches leverage advancements in the 60 GHz wireless frequency band to realize high bandwidth wireless links. While completely novel data center layouts provide the benefit of optimizing the placement of wireless links, they require a complete overhaul of existing data center infrastructure and cannot be easily merged with existing data center layouts.

Wireless data centers concepts have emerged from advancements in wireless technologies. Wireless frequencies at 60 GHz are capable of providing high data rates over distances of up to 10 meters. Highly directional antennas such as horned antennas or phased array antennas are used to establish wireless links only in one particular direction. These directional antennas enable spatial reusability due to favorable 60 GHz characteristics, however Line-of-Sight (LoS) communication is necessary to facilitate reliable communication [17]. Data center towers, metal frames, and cooling equipment all represent obstacles that could increase channel losses and prevent links from being established.
Several works have addressed these issues using 3D beamforming techniques to reflect 60 GHz signals off of metallic mirrors or through repeaters to achieve reliable communication [18] [19] [20]. The feasibility of establishing wireless 60 GHz links has been studied extensively, however using this technology within a data center environment remains an active area of study.

### 2.2.3 The 60 GHz Band

The radio frequency (RF) range commonly referred to as the 60 GHz band runs from 57 GHz to 64 GHz in the United States. This 60 GHz band is part of a larger frequency range known as the millimeter wave band, which constitutes all frequencies between 30 GHz and 300 GHz. This range of frequencies is known as the millimeter wave band due to the fact that the wavelengths for these frequencies are between roughly 1 mm to 10 mm in length. The 60 GHz portion of the frequency spectrum was made unlicensed by the Federal Communications Commission (FCC) in an attempt to stimulate growth and innovation in order to facilitate the commercialization of 60 GHz technologies [23]. This same portion of the frequency spectrum has been made available worldwide, with small differences in the starting and ending frequencies between various communications regulatory bodies. For example, in Europe the European Telecommunications Standards Institute (ETSI) has made the frequencies from 57 GHz to 66 GHz unlicensed. Due to the global acceptance in making the 60 GHz band open for unlicensed use, this frequency band has received much research and attention. Figure 4 depicts the various allocations of the 60 GHz band in different geographic regions. A common range of bandwidth centers on the spectrum mask at the 60.48 GHz frequency and is universally shared around the world.
The 60 GHz band is beneficial within a data center environment due to the large amount of bandwidth available and also because of advantageous channel characteristics. The high carrier frequencies at 60 GHz allow for transceivers to achieve multi-gigabit data rates. Moreover, the limited interference at 60 GHz and potential for spatial reuse makes 60 GHz technologies ideal for use within a wireless data center.

### 2.2.4 Existing 60 GHz Standards

Several standards have emerged to tackle various 60 GHz applications and communications. Standards such as WirelessHD [29], IEEE 802.15.3c [30], and ECMA 387 [31], are designed for short ranged wireless personal area networking (WPAN) applications. These standards serve to provide short high-speed links for multimedia scenarios. The WirelessHD standard for example, was designed for high definition video streaming in consumer products. Wireless local area networking (WLAN) standards addressing 60 GHz frequencies include the IEEE 802.11ad standard first published in 2012 and the WiGig standard first published in 2010. These standards address 60 GHz communications over larger distances and provide the natural evolution of Wi-Fi into the
60 GHz spectrum. Each of these standards makes use of the abundant bandwidth in the 60 GHz frequency band in order to provide high speed communication channels.

### 2.2.5 Channel Characteristics

Modeling 60 GHz frequencies is vital to the development of an accurate wireless data center design. In order to effectively model 60 GHz wireless links, the characteristics of the wireless channel must first be established. Wireless frequencies in lower frequency bands such as the ultra-high frequency (UHF) band (300MHz to 3 GHz) are able to propagate for miles and can penetrate solid obstacles without significant loss. This is due to the relatively large wavelength these frequencies exhibit. 60 GHz frequencies however, are operating at millimeter wavelengths, which limits both the distance they can propagate and the materials they can propagate through. The wavelengths of 60 GHz frequencies are around 5mm, meaning objects of only a few millimeters will effectively block the propagation of a 60 GHz wave, restricting wireless communication to LoS connections only.

For reliable 60 GHz communication to take place, a receiver antenna must receive a signal above a minimum receiver sensitivity level to accurately demodulate the wireless signal. This relationship can be expressed through the following equation.

\[
\text{Received Power} = \text{Transmit Power} + \text{Gains} - \text{Losses}
\]  \hspace{1cm} (1)

Where transmit power is the power that the transmitter module produces, gains represents the directionality and efficiency of the antenna, and losses represent any deterioration of the signal as it propagates from the transmitter to the receiver. The transmission power is dictated by FCC regulations, which limits the maximum average power level of indoor 60 GHz signals to 40 dBmi [27]. The antenna gain is dependent on the type of antenna used, such as an omnidirectional antenna, a horn antenna, or a phased antenna array. The last aspect of the equation is the losses incurred during the transmission. By understanding and mitigating the cause of loss in 60 GHz communications, better data rates can ultimately be achieved when the transmit power and antenna gain remains fixed.
Several factors contribute towards the propagation loss of 60 GHz signals and must be accounted for in order to obtain an accurate representation of the communication channel. 60 GHz signals operating at high data rates are around 55 dB worse than 2.4 GHz wireless links in terms of the signal to noise ratio (SNR) of the channel [9]. This difference can be attributed to two main factors, including free space path loss and the size of the channel. Free space path loss is the main form of loss 60 GHz frequencies face in LoS communication channels. The free space path loss can be expressed in terms of frequency and the distance between any two isotropic antennas shown in Equation 2.

\[ L_{FSL} = \left( \frac{4\pi R}{\lambda} \right)^2 \]  

Where R is the distance between the transmitter and receiver antennas and \( \lambda \) is the wavelength of the operating frequency. When converting to units of frequency and expressing Equation 1 in terms of dB it becomes:

\[ F_{FSL,\text{dB}} = 92.4 + 20 \log(f) + 20 \log(R) \]  

This free space path loss becomes significant at high frequencies and accounts for the majority of loss in millimeter wave bands such as the 60 GHz RF band. In addition to the attenuation due to free space, 60 GHz signals also face transmission losses through air due to atmospheric conditions. The 60 GHz frequency coincides with an absorption peak of oxygen, meaning molecules of O\(_2\) absorb 60 GHz frequencies. This absorption characteristic of oxygen along with absorption due to water vapor in the air results the attenuation of RF signals. This attenuation results in shorter propagation distances, however it also reduces the interference at other transceivers caused by 60 GHz signals enabling spatial reuse.

While path loss accounts for the majority of loss in the transmission of 60 GHz frequencies, the size of 60 GHz channels are roughly 100 times wider than 2.4 GHz channels. This creates a channel that is over 20 dB noisier at high data rates [25] and requires complex transceiver design. Additional sources of loss such as multi-path and fading effects are largely mitigated through the use of highly directional antennas [28] and the 60 GHz
characteristics. The directionality of the antennas greatly reduces indoor multi-path signal variations.

### 2.2.6 Antenna Characteristics

The antenna technology used in a 60 GHz transmission dictates the radiation pattern of the produced signal. Omni directional antennas propagate in all directions evenly, while directional antennas concentrate the transmitted power in a wireless signal in one specific direction. Directional antennas can be created by using a physical “horn” to direct the propagation of the waveform in one direction physically, or through the use of electronically steerable waveforms using phased array techniques. In the case of the horned antennas, the amount of directionality varies from wide-beam horn antennas with a broad radiation pattern, to narrow-beam horn antennas with narrower radiation patterns. These radiation patterns are typically measured in decibels isotropic (dBi), where the forward gain of the directional antenna is compared with a hypothetical isotropic antenna. Using a more directional antenna reduces the amount of power in unwanted directions and provides the ability to reuse the same frequency in other locations locally.

### 2.2.7 Spatial Reuse

An important characteristic of 60 GHz signals is their spatial reusability. Given that a 60 GHz signal is generated using a directional antenna, multiple transceivers can operate on the same frequency within proximities greater than 24 inches [9]. Spatial reuse isn’t possible with wireless communications in lower frequency ranges for the reason that their signals don’t attenuate in free space as rapidly as 60 GHz signals. The ability to form simultaneous communication channels on the same frequency at extremely high data rates is what makes the 60 GHz band attractive to use within a data center environment.

In order to obtain high bandwidth links for use within a data center environment, LoS must be maintained between transceivers [17]. Furthermore, within a data center, when these wireless transceivers and antenna modules are used in a ToR configuration, link blockage becomes a major problem. Dense rack deployments in standard data center layouts presents
limitations for the formation of LoS links at the ToR level. Only neighboring or geographically close racks are able to establish reliable 60 GHz links [26]. This presents a challenge for ToR transceivers that necessitate communications across multiple isles. On the other hand, a medium access challenge exists in determining what non-interfering links can be established in the same channel at the same time. Each of these challenges and considerations are addressed in the proposed approach.

2.3. Significance

This work will contribute towards the investigation into wireless data centers utilizing 60 GHz frequencies by building upon previous wireless data center works. A completely wireless data center will be explored with the goal of addressing major data center design principles such as energy efficiency, cabling complexity, oversubscription, scalability, and overall performance. Several novel wireless data center techniques mentioned in previous works will be incorporated into a solution that addresses contemporary data center networking challenges.
Chapter 3

Wireless Data Center Network Design

The architecture of the rack-to-rack wireless DCN is arranged into several parts. First the wireless topology will be explained in depth, along with several important design considerations. Next, the 60 GHz antenna technology adopted in this work is examined. The proposed link establishment mechanisms are then explained and supported. Following the link establishment is a description of the chosen network protocols used to realize the wireless DCN approach. Finally, this chapter will conclude with a section devoted to the method of power modeling used to evaluate the power consumption of the DCNs.

3.1. Architecture

The proposed wireless data center network architecture is comprised of several sections, including a description of the topology, the antenna and 60 GHz technologies employed, the method of link selection, and the communication protocols used. This section will explain both the proposed wireless architecture and the methodologies utilized in the development of the architecture.

3.1.1 Topology

The wireless data center network uses 60 GHz links to connect racks within a data center at the ToR level. A completely wireless ToR level is adopted, meaning any two racks have the capability of communicating using 60 GHz wireless transceivers. Servers within a rack are connected using traditional wired links to ToR network switches which are augmented with a ToR wireless module. Each ToR wireless module contains a transceiver and antenna capable of communicating with any other ToR wireless module within the data center. The wireless data center is physically bound by the distance that a 60 GHz wireless signal can reliably transmit to any other module. Only single hop wireless links are explored in order to simplify the routing and link establishment mechanisms. Data center racks are laid out
in traditional configurations, with isles running between rows of data center racks. A visualization of the data center layout is illustrated in Figure 5.

![Data Center Visualization](image)

Figure 5: Data Center Visualization

The wireless transceiver and antenna module sit atop each of the racks within the data center. The horn antennas are mechanically steered and are oriented during the formation of a link so that the transmitter and receiver can communicate with each other. Each ToR module is assigned an ID and the geographic location of all ToR modules and orientations necessary to form links are considered known. A top down view of the data center geographic layout is shown in Figure 6.
Each box in Figure 6 represents one data center rack. There are 10 racks arranged in a single row and two columns of 8 rows, totaling 160 racks. Each rack is a 1 meter by 1 meter wide. 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 data center room for an averaged sized data center according to the Data Center Institute’s Data Center Size and Density Standard [24].

The decision to make the ToR level completely wireless is influenced by several design considerations. First, the link speeds between the ToR and Aggregation levels in an average data center are around 1 Gigabit per second, with faster data centers using links at 10 Gigabits per second to connect the ToR level. These link speeds are based upon the speeds of available commercial data center networking switches [37]. 60 GHz wireless links have been shown to sustain such data rates. Moreover, creating a wireless layer at the ToR level alleviates the vast majority of the cabling complexity problems, as inter-rack, aggregation, and core level connections and cabling can be ignored. The reduction in the amount of cabling also contributes to more space above and between racks, freeing up critical LoS
paths necessary for reliable wireless communication. Another reason for making the ToR level completely wireless is to be able to reduce the number of levels of aggregation. Reducing the number of levels of aggregation both alleviates oversubscription problems and allows for the removal of power hungry aggregation and core level switches. Oversubscription is mitigated by allowing two racks to be able to communicate with other racks at the same time without creating contention with an aggregation or core level switch. This produces both a less congested and more power efficient network. Several levels of aggregation are collapsed into a single one-hop wireless layer. While the wireless network cannot provide the same cross sectional bandwidth afforded by wireline networks, this work argues that the majority of the bandwidth provided by wired networks goes unused during normal use. Hence, the wireless interconnection framework with a smaller cross-sectional bandwidth should be able to cater to the demands while providing significant energy savings. A wireless architecture allows the creation and establishment of links only when they are necessary. This eliminates the wires and switches needed to aggregate traditional wired based networks.

The decision to leave intra-rack server connections wired was due to the fact that many existing rack technologies already provide wired connections in addition to other services such as common power and cooling resources. This concept is especially true with blade type servers which plug into existing rack infrastructures. By leaving the intra-rack system unmodified, the ability to adopt 60 GHz wireless modules into existing systems becomes practical. Additionally, large metal rack frames form an obstacle for wireless antennas at the server level to be able to easily form one-hop links to a ToR module, limiting the wireless level to the ToR.

### 3.1.2 Antenna Technology

Inside each of the ToR wireless modules is a transceiver and an accompanying antenna. A horn antenna is used to provide directionality to each of the wireless modules. A minimum amount of directionality is necessary to enable the connection of distant links within a data center with a constant transmit power. A directional horn antenna is chosen to be able to
connect the most distant racks within a data center at the fastest achievable data rate. The selection of this directional antenna is supported in the next chapter. Horn antennas are chosen due to their wide availability and proven capabilities. While on chip antennas and phased arrays may prove to be better antenna technologies in the future, these antennas within the 60 GHz band are still emerging and are not yet widely available for use. Furthermore, several existing wireless works successfully made use of horn antennas to demonstrate wireless connectivity at 60 GHz [9] [10]. Horn antennas provide a reliable starting point to test the feasibility of a wireless data center at 60 GHz. The investigation of alternative antenna technologies is left to future work.

### 3.1.3 Establishment of Wireless Links

A completely wireless ToR level means any ToR wireless module will be able to connect to any other wireless ToR module within the data center. This however, doesn’t mean that the ToR level is fully connected. Whenever a ToR wireless module connects to another wireless module, neither of these modules can connect to any other wireless module on the same wireless channel. Furthermore, although multiple wireless links can be formed at the same time, a wireless link has the possibility of creating interference for other transmitting wireless modules. Intelligent link selection is necessary to prevent interference and to optimize the establishment of links.

The link selection can be thought of as a scheduling problem. Given a list of application demands over a period of time, wireless links must be established and removed to satisfy bandwidth demands. These application demands can be generated through trace driven approaches or predictive mechanisms. Using this list of known demands, wireless links are generated until an optimal state is achieved. An optimal state can defined as a state in which the maximum amount of data is transferred globally across the entire data center. Given the large number of possible combinations of links that can be established and the large set of application demands, this scheduling problem becomes NP-Complete in computational complexity. A simple greedy approach is taken to connect the ToR wireless modules with
the largest demands on a first-come first-serve scheme. The greedy algorithm used is depicted in Figure 7.

![Greedy Algorithm Flowchart](image)

**Figure 7: Greedy Algorithm Flowchart**

The algorithm establishes as many non-interfering links as possible on a first-come first-served basis until all demands are exhausted or the number of available channels runs out. The list of unaddressed demands is ordered by the start time of each demand. During the assignment of a link, if every channel contains another interfering link, the current link cannot be established and the demand is skipped. In a real world scenario this skipped demand would be rescheduled in a following time period and its priority would increase over other demands. This method of rescheduling and prioritization is left to future work. Once a link is determined to be unassignable it is no longer considered and that demand is left uncompleted. While this greedy first-come first-served approach may not reach an optimal state of selected links, it serves to achieve a good enough state with minimal
computational effort. The validity of this greedy approach can be determined through a comparison and analysis against similarly sized wired networks.

3.1.4 Communication Protocols

A wireless 60 GHz physical layer protocol is necessary to be able to establish reliable connections between ToR modules. Rather than reinventing a completely novel protocol from scratch, the IEEE 802.11ad stands out as a suitable candidate. The 802.11ad standard is designed for local area networking at and beyond distances of 10 meters. This standard defines a physical layer protocol that supports beamforming and also supports very high data rates in both a single channel (SC) and OFDM mode of operation. The 802.11ad SC and OFDM rates are shown below in Table 3 and Table 4 [25].

<table>
<thead>
<tr>
<th>MCS Index</th>
<th>Modulation</th>
<th>NCBPS</th>
<th>Repetition</th>
<th>Code Rate</th>
<th>Data Rate (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>π/2-BPSK</td>
<td>1</td>
<td>2</td>
<td>1/2</td>
<td>385</td>
</tr>
<tr>
<td>2</td>
<td>π/2-BPSK</td>
<td>1</td>
<td>1</td>
<td>1/2</td>
<td>770</td>
</tr>
<tr>
<td>3</td>
<td>π/2-BPSK</td>
<td>1</td>
<td>1</td>
<td>5/8</td>
<td>962.5</td>
</tr>
<tr>
<td>4</td>
<td>π/2-BPSK</td>
<td>1</td>
<td>1</td>
<td>3/4</td>
<td>1155</td>
</tr>
<tr>
<td>5</td>
<td>π/2-BPSK</td>
<td>1</td>
<td>1</td>
<td>13/16</td>
<td>1251.25</td>
</tr>
<tr>
<td>6</td>
<td>π/2-QPSK</td>
<td>2</td>
<td>1</td>
<td>1/2</td>
<td>1540</td>
</tr>
<tr>
<td>7</td>
<td>π/2-QPSK</td>
<td>2</td>
<td>1</td>
<td>5/8</td>
<td>1925</td>
</tr>
<tr>
<td>8</td>
<td>π/2-QPSK</td>
<td>2</td>
<td>1</td>
<td>3/4</td>
<td>2310</td>
</tr>
<tr>
<td>9</td>
<td>π/2-QPSK</td>
<td>2</td>
<td>1</td>
<td>13/16</td>
<td>2502.5</td>
</tr>
<tr>
<td>10</td>
<td>π/2-16QAM</td>
<td>4</td>
<td>1</td>
<td>1/2</td>
<td>3080</td>
</tr>
<tr>
<td>11</td>
<td>π/2-16QAM</td>
<td>4</td>
<td>1</td>
<td>5/8</td>
<td>3850</td>
</tr>
<tr>
<td>12</td>
<td>π/2-16QAM</td>
<td>4</td>
<td>1</td>
<td>3/4</td>
<td>4620</td>
</tr>
</tbody>
</table>

Table 3: Single Channel 802.11ad data rates [25]

<table>
<thead>
<tr>
<th>MCS Index</th>
<th>Modulation</th>
<th>NBPSC</th>
<th>NCBPS</th>
<th>NDBPS</th>
<th>Code Rate</th>
<th>Data Rate (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>SQPSK</td>
<td>1</td>
<td>336</td>
<td>168</td>
<td>1/2</td>
<td>693.00</td>
</tr>
<tr>
<td>14</td>
<td>SQPSK</td>
<td>1</td>
<td>336</td>
<td>210</td>
<td>5/8</td>
<td>866.25</td>
</tr>
<tr>
<td>15</td>
<td>QPSK</td>
<td>2</td>
<td>672</td>
<td>336</td>
<td>1/2</td>
<td>1386.00</td>
</tr>
<tr>
<td>16</td>
<td>QPSK</td>
<td>2</td>
<td>672</td>
<td>420</td>
<td>5/8</td>
<td>1732.50</td>
</tr>
<tr>
<td>17</td>
<td>QPSK</td>
<td>2</td>
<td>672</td>
<td>504</td>
<td>3/4</td>
<td>2079.00</td>
</tr>
<tr>
<td>18</td>
<td>16-QAM</td>
<td>4</td>
<td>1344</td>
<td>672</td>
<td>1/2</td>
<td>2772.00</td>
</tr>
<tr>
<td>19</td>
<td>16-QAM</td>
<td>4</td>
<td>1344</td>
<td>840</td>
<td>5/8</td>
<td>3465.00</td>
</tr>
<tr>
<td>20</td>
<td>16-QAM</td>
<td>4</td>
<td>1344</td>
<td>1008</td>
<td>3/4</td>
<td>4158.00</td>
</tr>
<tr>
<td>21</td>
<td>16-QAM</td>
<td>4</td>
<td>1344</td>
<td>1092</td>
<td>13/16</td>
<td>4504.50</td>
</tr>
<tr>
<td>22</td>
<td>64-QAM</td>
<td>6</td>
<td>2016</td>
<td>1260</td>
<td>5/8</td>
<td>5197.50</td>
</tr>
<tr>
<td>23</td>
<td>64-QAM</td>
<td>6</td>
<td>2016</td>
<td>1512</td>
<td>3/4</td>
<td>6237.00</td>
</tr>
<tr>
<td>24</td>
<td>64-QAM</td>
<td>6</td>
<td>2016</td>
<td>1638</td>
<td>13/16</td>
<td>6756.75</td>
</tr>
</tbody>
</table>

Table 4: OFDM 802.11ad data rates [25]
Where the MCS is the number assigned to that modulation and coding scheme, modulation is the type of modulation employed, \( N_{BPSC} \) is the number of coded bits per single carrier, \( N_{CBPS} \) is the number of coded bits per symbol, \( N_{DBPS} \) is the number of data bits per symbol, the code rate is the ratio of data bits to the number total bits used including bits used for error correction, and the data rate is the maximum sustainable data rate for that MCS. The maximum achievable data rate using SC is 4.62 Gbps and for OFDM the maximum achievable data rate 6.75675 Gbps. Due to the high data rates and transmission distances above 10 meters, the IEEE 802.11ad standard is adopted as the 60 GHz physical layer protocol used in this work.

The wireless 802.11ad rate used is dependent on the interference and the transmission loss observed at the receiver module. The transmission losses between any two transceivers is highly dependent on the distance between the transceivers. As the distance between transceivers increases, a lower received signal strength (RSS) will be observed at the receiver, yielding an increase in interference of the transmitted data. Furthermore, due to the fact that multiple transmitters will potentially be operating at the same time, interference from other signals must also be accounted for. If this signal to interference plus noise ratio (SINR) becomes large enough, bit errors will emerge in the received data. The SINR and the 802.11ad MCS used in the wireless communication result in the bit error rate (BER) observed at the receiver module. If this computed BER exceeds an allowable bit error rate, the received data may no longer be valid and the packet must be retransmitted. The sensitivity for each MCS is defined in the 802.11ad standard as the SINR power level down to which 99% of a 4096 byte packet is successfully received. This minimum sensitivity threshold coincides with a bit error rate of 3 \( \times \) 10\(^{-7} \). A change to a different MCS is used to transmit the data at a slower and more stable data rate when the SINR at the receiver module exceeds a threshold based upon the 802.11ad standard. The 802.11ad standard defines -81dB of thermal noise for a 2.16 GHz channel and 15dB attributed to implementation losses. A more stable MCS requires changing either the coding rate or the modulation scheme. A more stable coding rate uses a higher fraction of bits in a transmission for error detection and correction. A more stable modulation scheme uses a fewer number of symbols, which in turn results in an easier differentiation between
symbols at the receiver module. The ability to adapt the MCS to account for various levels of interference and noise makes the wireless channel more robust as a whole. Each of these aspects makes the 802.11ad physical layer standard a good choice for use within a data center.

The 802.11ad MAC layer protocol is adopted in this work, as the 802.11ad standard defines both the physical layer and the MAC layer protocols. The medium access at a higher level is dictated by the optimization of spatial reuse by the nature of the scheduling algorithm. The scheduling algorithm facilitates the creation of spatial reuse afforded by the 60 GHz links and ensures the avoidance of interference by establishing non-interfering links. The data center wireless modules are statically placed, meaning the amount of interference generated at any node can be estimated and considered prior knowledge based upon the currently transmitting nodes. This mechanism is used to ensure only non-interfering links are established during the analysis of this architecture.

The Transmission Control Protocol (TCP) is adopted as the transport layer protocol for its widespread use and well known characteristics. TCP traffic is generated at source racks and captured at destination racks to simulate application traffic. TCP forms a common and reliable mechanism for the delivery of packets within the data center. The nature of TCP traffic is well known and used as a starting point for this work. Alternative transport layer protocols are left for future work.

3.2. Power Modeling

Establishing an accurate power consumption model for a data center’s entire power portfolio is a complicated endeavor. 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 geographic location, the efficiency of the data center’s building layout, and the level of reliability of the data center. As this work’s primary focus is the data center’s network, only the network components will be modeled and evaluated. This work leverages its power consumption improvements from the removal of the core and aggregation switching levels. By collapsing the tree based
wired network into a single wireless level of one-hop links, the large and expensive core and aggregation switches can be left out of the DCN. Small wireless transceivers take the place of those switches at a fraction of the power consumption.

Modern commercial data center network switches manufactured by Cisco are used to establish accurate projections for the power consumption of the network infrastructure. Both the typical and maximum power consumption figures are captured from a number of Cisco switches. These values are used to estimate the power consumption of a data center’s network were it to be physically constructed. While not a perfect solution, the estimated power consumption figures are all generated from actual listed devices, allowing for a more realistic estimation. Platform specific switches are used for each level of link aggregation and are shown in Figure 8.

![Cisco Nexus Platforms for Three Tier Network](image)

Figure 8: Cisco Nexus Platforms for Three Tier Network [37]
Switches from each platform level are appropriately chosen based on the number of links required and the link speed necessary to model the power consumption of the wired networks. An overview of the power consumption of the network switches is shown in Table 5.

<table>
<thead>
<tr>
<th>Switches</th>
<th>Component</th>
<th>Wired 40/10</th>
<th>Wired 1/10</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max (W)</td>
<td>Typical (W)</td>
<td>Max (W)</td>
</tr>
<tr>
<td>Cisco 7702 (Core Level) [38]</td>
<td>Supervisor</td>
<td>265</td>
<td>137</td>
</tr>
<tr>
<td></td>
<td>I/O Cards</td>
<td>740</td>
<td>650</td>
</tr>
<tr>
<td></td>
<td>Fan Tray</td>
<td>300</td>
<td>50</td>
</tr>
<tr>
<td>Cisco 9508 (Aggregation Level) [39]</td>
<td>Supervisor</td>
<td>80</td>
<td>69</td>
</tr>
<tr>
<td></td>
<td>System Controllers</td>
<td>50</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>I/O Cards</td>
<td>1440</td>
<td>1200</td>
</tr>
<tr>
<td></td>
<td>Fabric Modules</td>
<td>1004</td>
<td>704</td>
</tr>
<tr>
<td></td>
<td>Fan Tray</td>
<td>750</td>
<td>528</td>
</tr>
<tr>
<td>Cisco 9300 (Access Level) [40]</td>
<td>Switch</td>
<td>650</td>
<td>210</td>
</tr>
</tbody>
</table>

Table 5: Switch Power Consumption Overview

The power consumption of each wired DCN can be established from the addition of the power consumptions for each network layer. This total power consumption is shown in Equation 4.

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

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. The power consumption of the core switch can be broken down even further into individual components such as I/O cards, fan trays, and supervisors as shown in Equation 5.

\[ P_{core} = P_{I/O\, Cards} + P_{Fan\, Tray} + P_{Supervisors} \]  

A similar breakdown is possible for the aggregation level switch with the inclusion of the fabric and system controllers as shown in Equation 6.

\[ P_{agg} = P_{I/O\, Cards} + P_{Fan\, Tray} + P_{Supervisors} + P_{Fabric} + P_{Sys\, Controller} \]
The Fabric and I/O cards reflect the necessary cards used to realize a ThreeTier configuration with 160 racks. The access level switches aren’t modularized and thus contains only a single reported power consumption figure. The use of actual reported power consumption figures for each level of the DCN serve to provide an accurate estimate of the wired network power consumption of a real data center were it physically constructed using commodity network switches.

The power consumption of the 60 GHz wireless modules is based upon a survey of developing 60 GHz wireless transceiver technologies. As 60 GHz technology matures, wireless transceivers operating at these frequencies will become more power efficient and widely available. Table 6 summarizes current emerging 60 GHz transceiver technologies and illustrates the fact that these transceivers consume only hundreds of milliwatts to operate at gigabit data rates.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Distance</th>
<th>TX Power Consumption</th>
<th>RX Power Consumption</th>
<th>Data Rate</th>
<th>Modulation Scheme</th>
<th>Antenna</th>
</tr>
</thead>
<tbody>
<tr>
<td>[32]</td>
<td>1m-2m</td>
<td>156mW</td>
<td>107mW</td>
<td>15Gbps (4 channels)</td>
<td>OOK</td>
<td>On-Chip</td>
</tr>
<tr>
<td>[5]</td>
<td>2m</td>
<td>131mW</td>
<td>101mW</td>
<td>6Gbps</td>
<td>BPSK</td>
<td>Horn</td>
</tr>
<tr>
<td>[6]</td>
<td>3m</td>
<td>170mW</td>
<td>138mW</td>
<td>5Gbps</td>
<td>QPSK</td>
<td>Horn</td>
</tr>
<tr>
<td>[33]</td>
<td>2m</td>
<td>374mW</td>
<td>151mW</td>
<td>3.5Gbps</td>
<td>BPSK</td>
<td>Horn</td>
</tr>
<tr>
<td>[34]</td>
<td>-</td>
<td>173mW</td>
<td>189mW</td>
<td>7Gbps</td>
<td>QPSK</td>
<td>On-Chip</td>
</tr>
<tr>
<td>[35]</td>
<td>1m-3m</td>
<td>822mW</td>
<td>547mW</td>
<td>2Gbps</td>
<td>BPSK</td>
<td>-</td>
</tr>
<tr>
<td>[36]</td>
<td>-</td>
<td>135mW</td>
<td>-</td>
<td>5Gbps</td>
<td>QPSK</td>
<td>-</td>
</tr>
<tr>
<td>[7]</td>
<td>10m</td>
<td>190mW</td>
<td>195mW</td>
<td>630Mbps</td>
<td>OFDM-QPSK</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 6: 60 GHz Transceiver Technologies

A conservative power estimate of 1W for the maximum power consumption and 500mW for the typical power consumption for the wireless module is adopted in this work. This places the majority of surveyed transceivers under the power figure used for the wireless module. Additionally, the 500mW estimation is for an actively communicating module. Many transceivers will not be actively communicating at any given point in time, meaning the use of 500mW as the power consumption for every module is a worst case scenario in which all wireless modules are active all at the same time. Furthermore, as technology
improves, the overall power consumption of 60 GHz transceivers is expected to remain at or around the same order of magnitude as all of the transceivers surveyed in this work.
Chapter 4

Results & Analysis

This section is broken up into several pieces, covering all generated results and their significance. First the simulation platform is outlined in depth, along with the accompanying modifications implemented to realize the proposed wireless DCN architecture. Then a study on the antenna gain is covered to establish several physical characteristics of the wireless DCN. Several wireless DCN implementations are then compared to two wired DCNs. The scalability of the wireless DCN is addressed and a section on the limitations of this wireless DCN approach concludes this chapter.

4.1. Simulation Platform

The proposed wireless data center network is simulated using a modified version of the Network Simulator 3 (NS-3) [21]. A network simulator is chosen for the reason that the proposed work is primarily comprised of a network with complex links. The data center network is the primary focus of this work, making NS-3 particularly suitable as a research platform. Additionally, NS3 provides support for both wired and wireless simulations, allowing both to be compared using the same simulation platform. Furthermore, NS-3 simulates both wireless propagation as well as the network level characteristics. Only simulating the wireless 60 GHz propagation characteristics would fail to capture network level features. Similarly, modeling a data center network with traditional Wi-Fi links would fail to capture the complexities of the 60 GHz channel and spatial reuse. Only through the simulation of both can an accurate wireless data center network be established.

The modified NS-3 simulation platform extends the additions contributed by prior work on wireless data centers. The authors in [9] implemented support for the formation of 60 GHz links using the 802.11ad physical layer standard. Furthermore, the authors verified the accuracy of their implementation using physical layer measurements from prototype 60 GHz hardware. Accurate interference modeling, bit error rate estimations, and directional
antenna modeling are also provided by the authors in [9]. These extensions to the NS-3 platform provide a solid foundation from which this work builds upon.

Additional modifications to the NS-3 simulator are made to realize a completely wireless approach. This work extends the link selection criteria for forming wireless links to facilitate the creation of a large number of simultaneous wireless links. Furthermore, modifications to the 802.11ad OFDM physical layer channel allowed for the simulation of multiple channels operating at gigabit speeds to be established.

### 4.2. Antenna Gain

In addition to the 60 GHz transceiver, an antenna must be used to ensure high directionality and in turn the reliability of the wireless link. A horn antenna model is simulated using the NS-3 platform. The directionality of a horn antenna is measured by its gain relative to an isotropic radiator, with wide-beamed antennas resulting in a wider angle of signal propagation and narrow-beamed antennas resulting in narrower angles of signal propagation. The result of a narrower beam is a larger amount of radiated power in a single direction compared to a similar wide beam antenna using the same maximum transmit power. This results in a greater signal strength at the receiver, reducing bit errors and allowing for a better modulation and coding scheme (MCS) to be used, yielding faster data rates. To determine what level of minimum directionality is necessary for any ToR wireless module to communicate with its farthest possible ToR destination, a set of simulations are performed. Two wireless 60 GHz network devices are simulated and the average throughput is measured at a number of different distances from 1 to 20 meters. This ending distance of 20 meters is around the average longest distance a wireless module will have to transmit to reach a transceiver on an opposite edge of the datacenter. Additionally, this simulation is repeated for varying antenna gains from a gain of 0 dBi (representing an Omni-directional antenna), to a gain of 22 dBi (representing a highly directional antenna). At each distance and for all antenna types the simulation is repeated 5 times and the results are averaged. The average data rates produced are shown below in Figure 9.
Figure 9: Antenna Distance vs. Throughput Comparison

As the distance between the transmitter and receiver increases, a decrease in the achievable data rate is evident. This effect is shown to be more pronounced with antennas of lower directionality, with the Omni-directional antenna at a gain of 0 dBi failing to reach gigabit data rates as soon as the distance exceeds 2 meters. At an antenna gain of 20 dBi, the achievable data rates are nearly consistent over every distance, however they begin to fall off at 19 meters. It was found that at a gain of 22 dBi, there is no noticeable difference between the achievable data rates at 1 meter and the data rates at 20 meters. The abrupt jump in data rates seen in the antenna with a gain of 15 dBi is due to a physical layer rate selection change in the MCS’s due to an increase in bit errors. A bit error rate of $3.0 \times 10^{-7}$ is used for all rates and antennas.

Although an antenna with a gain of 22 dBi is shown to form a stable communication channel across the entire width of the data center, higher directionality may be necessary. The ability to maximize the amount of spatial reuse is crucial to the establishment of a large number of simultaneous links. As wireless beam-widths become narrower, interference with other wireless transceivers is reduced in all other directions and increased in the direction of the primary lobe. This reduces the interference at neighboring transceivers and only increases interference with other transceivers in a singular direction. Further work is necessary to determine an optimal amount of antenna gain and directionality best suited
for a data center environment. The antenna gain of 22 dBi serves as the lowest amount of directionality necessary to be able to reach all other potential wireless transceivers at the maximum achievable data rate.

### 4.3. Application Demands & Traffic Generation

The wireless DCN is evaluated using a list of application demands. These demands outline traffic which needs to move within the network over a period of time. The application demands include information specifying the source of the application traffic, the destination of the application traffic, the amount of traffic that will be generated, and the data rate at which traffic is generated. Application demands are representative of the aggregate traffic requirements of all servers within a rack, as the network being studied is at the ToR level. The list of application demands also includes the time at which the demand starts generating traffic. An example traffic demand is shown in Table 7 below.

<table>
<thead>
<tr>
<th>Start Time (Sec)</th>
<th>Source Node</th>
<th>Destination Node</th>
<th>Volume of Data (Bytes)</th>
<th>Data Rate (Gbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.567</td>
<td>10</td>
<td>34</td>
<td>584273080</td>
<td>0.792</td>
</tr>
</tbody>
</table>

Table 7: Example Application Demand

Where the start time represents the time during the simulation when the application begins generating traffic, the source node is the source ToR network device, the destination node is the destination ToR network device, the amount of data is the number of bytes that are generated, and the data rate is the rate at which data is generated at the source node. This list of demands is known beforehand and provided to the simulation platform prior to the evaluation of the network. Each DCN is responsible for satisfying as many application demands as possible by routing the generated traffic from source to destination ToR’s. The data set used contains 1000 application demands generated between 0 and 100 seconds, with random data sizes between 1 MB and 1 GB and random data rates between 10 Mbps and 1 Gbps. The data sizes reflect the volume of ToR traffic and the data rates reflect the rate applications produce traffic within a rack. All traffic generated uses the TCP protocol within the data center network, with a maximum transmission unit (MTU) of 10,000 bytes. The MTU is purposefully made large to ensure wireless fairness and to allow for a greater
efficiency of the wireless transmission. With 802.11ad OFDM rates reaching a maximum of 6.67 Gbps, leaving the MTU small will create unnecessary overheads that will hinder network performance. Additionally, the wireless environment is relatively stable as each transceiver remains fixed geographically, reducing the number of bit errors and subsequently the need for retransmission. This combination of high data rates and relatively stable environment allows for a higher MTU to be advantageous in wireless transmissions.

### 4.4. Wireless DCN Performance

Several different DCNs are created and evaluated using the generated list of 1000 application demands. Performance is measured over several metrics such as the number of completed demands, the average link throughput achieved, and the power consumption of the DCN. The number of completed demands represents the number of application demands that the DCN is able to complete over a given time frame. This metric best encapsulates the contribution of a number of factors and gives an overall impression of how well the DCN performed. Factors such as the type of network used, the amount of oversubscription present, and the speed of network links all contribute to the number of satisfied demands.

#### 4.4.1 Ideal DCN

An ideal ThreeTier wired network is simulated to represent the best achievable performance using a ThreeTier wired network. This network is used as an ideal point of comparison to be used to evaluate the achieved performance of each of the simulated DCNs. The ideal wired network uses links of much greater bandwidth than would normally be observed in a data center and are several orders of magnitude greater than the fastest DCN simulated. Each of the wired links in the ideal network are simulated to be able to sustain 1 Tbps data rates. The simulation is conducted over 100 seconds with 1000 application demands. The number of completed demands over 100 seconds are shown in Figure 10.

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The Ideal DCN completed 860 out of the list of 1000 demands over the 100 seconds of simulated time. The average throughput of all completed demands is 522.925 Mbps, and the average throughput of the entire list of 1000 demands is 481.54 Mbps. These results are summarized in Table 8.

<table>
<thead>
<tr>
<th>Total Number of Demands</th>
<th>Demands Completed</th>
<th>Throughput of Completed Demands (Mbps)</th>
<th>Throughput of all Demands (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>860</td>
<td>522.925</td>
<td>481.54</td>
</tr>
</tbody>
</table>

Table 8: Ideal DCN Results

The throughput of competed demands is an average throughput of only the demands that finished within 100 seconds. The throughput of all demands represents the average throughput of the entire list of demands regardless of whether the demand was completed, not started, or in progress. The ideal network didn’t complete all 1000 demands due to the fact that for some of the demands, the rate of generation and the amount of data to be generated placed the minimum completion time outside of the simulated 100 seconds. This occurrence is true for many of the demands towards the end of the 100 second simulation period. For example, if a demand is scheduled to start at time 97 seconds, with a generation rate of 0.1 Gbps, and must send 50 MB of data, the time at which the demand will finish generating data is at 101 seconds. Assuming the data can be sent from source to destination
instantaneously, this still places the completion time outside of the 100 second simulation window. The ideal DCN will serve as a reference to compare the performance of other DCNs.

### 4.4.2 Single Channel Wireless DCN

In addition to the proposed wireless DCN, two wired ThreeTier DCNs are simulated using the same list of demands over 100 seconds. One wired network consists of 1 Gbps links between the ToR access level switches and the middle level aggregation switches, and 10 Gbps links between the aggregation level and top level core switches. This wired network will be identified as the 1/10 wired network as it employs 1 Gbps and 10 Gbps links. This wired network is representative of a conventional data center using standard commercial equipment and link speeds. The simulated 1/10 wired network consists of 160 access level switches, 2 aggregation level switches, and 2 core level switches. This network has an oversubscription ratio of 4:1 with 160 Gbps of downstream aggregate bandwidth and 40 Gbps of aggregate upstream bandwidth.

The second wired network also follows a ThreeTier configuration with 10 Gbps links between the ToR access level switches and the middle level aggregation switches, and 40 Gbps links between the aggregation level and top level core switches. This wired network will be identified as the 10/40 wired network as it employs 10 Gbps and 40 Gbps links. This wired network is representative of a higher end data center using faster and more expensive switches. The simulated 10/40 wired network consists of 160 access level switches, 2 aggregation level switches, and 2 core level switches. This network has an oversubscription ratio of 10:1 with 1600 Gbps of downstream aggregate bandwidth and 160 Gbps of aggregate upstream bandwidth.

The wireless DCN is first simulated using a single 60 GHz channel using the 802.11ad SC rates. 160 ToR wireless modules are connected to their respective access level switches and all start in a non-transmitting mode of operation. Links are established in an on demand fashion using the simple greedy approach outlined in section 3. Whenever an application demand finishes the wireless transmitters cease communication and return to their non-
transmitting states. This wireless DCN along with the two wired DCNs are simulated for 100 seconds. The number of completed demands for each type of DCN are shown in Figure 11.

![Figure 11: Number of Completed Demands (SC)](image)

The 1/10 DCN completes a maximum of 838 demands, the 10/40 DCN completes a maximum of 860 demands, and the SC wireless DCN completes a maximum of 211 demands. Only using a single wireless channel yielded roughly one fourth of the number of links the wired networks completed. One may assume that the wireless DCN doesn’t sustain link speeds necessary to complete demands, however looking at the average throughput of completed links in Figure 12 shows otherwise.
The SC wireless DCN has the highest average throughput of all DCNs, meaning the wireless link speed isn’t the reason for the lower number of demands completed. Another possible cause is that the SC wireless DCN completed links over time differently than the wired DCNs. The number of completed demands for the SC wireless over time are shown in Figure 13.
Although the single channel wireless DCN completed demands at a consistent rate, the number of demands completed per second is significantly less than the wired networks. The reason for this is due to the maximum number of sustainable non-interfering links that can be formed. The number of links formed over time during the simulation of the wireless DCN is shown below in Figure 14.

The theoretical maximum number of links that can be formed using the SC DCN is the maximum number of pairs of ToR wireless modules. For 160 racks the maximum number of pairs that can be formed is 80. After 10 seconds of initial link formations, the number of links formed in Figure 14 is roughly 43 on average. This number is well below the theoretical 80 pairs that could be made because of two reasons. The first reason is the fact that the assignment of source destination pairs is random and there is no guarantee that a state where there are 80 actively communicating pairs is present in the simulation window. The second reason is that as more and more links are established, there is an increasing chance that a potential new link will result in interference and won’t be established. This is a result of the greedy link establishment mechanism not guaranteeing that the optimal set of links are established.
To improve the performance of the wireless DCN, 4 unique wireless channels are simulated. These 4 channels are simulated using the faster 802.11ad OFDM rates instead of the SC rates. The 4 wireless 60 GHz carrier frequencies used in each of the channels are centered around 58.32 GHz, 60.48 GHz, 62.64 GHz, and 64.80 GHz. Each channel contains approximately 1.83 GHz of channel bandwidth. The whole 4-Channel wireless DCN uses 4 times the amount of bandwidth that the SC DCN used, with the expectation that the network will complete 4 times the number of demands. The simulation results of the 4-Channel wireless DCN over 100 seconds and with 1000 application demands are shown in Figure 15.

Figure 15: Number of Completed Demands (4-Channel)

The wired DCNs remain unchanged at 838 and 860 completed demands for the 1/10 and 10/40 respectively. The 4-Channel wireless DCN completes 732 demands over 100 seconds. While the 4-Channel wireless network performed much better than the SC wireless DCN, the number of completed demands still doesn’t surpass the conventional 1/10 wired ThreeTier DCN. Despite the fact that the 4-Channel wireless DCN can support 6.67 Gbps data rates on each channel, the network still only completes 732 demands. The reason for this occurrence is because there are still links that cannot be established due to
interference with existing links even with 4 separate channels. Furthermore, each of the channels support much larger data rates than what the application demands necessitate. Each demand only generates data between 0 and 1 Gbps, meaning a wireless link at 6.67 Gbps is more than enough to handle a single demand. The wireless links may not all be operating at their highest MCS and data rate, however only the first 2 OFDM MCS’s fall below a 1 Gbps data rate. This means the OFDM rates are unlikely the cause of the difference between the wired and wireless DCNs. Observing the number of demands completed on each channel in the 4-Channel wireless DCN reveals that more channels are necessary. The number of completed demands on each of the wireless channels are shown in Figure 16.

![Figure 16: Number of Completed Demands per Channel (4-Channel)](image)

Each subsequent wireless channel completes fewer demands than the channel before it, however channel 4 is still completing over 125 demands, with many demands left uncompleted when compared to the wired DCN. More wireless channels are necessary to be able to demonstrate comparable results with the two wired DCNs.
4.4.4 12 Channel Wireless DCN

In order to overcome the channel limitations of the 4-Channel DCN approach, this work proposes dividing up the number of OFDM subcarriers in each channel to accommodate multiple application demands. An OFDM channel defined in the 802.11ad standard uses 512 total subcarriers broken up into 336 data subcarriers, 16 pilot subcarriers, 3 direct current subcarriers, and 157 null subcarriers. If the data subcarriers are divided into 4 groups with each group able to handle an individual demand’s traffic, 4 times the number of demands could be transmitted, with each group of subcarriers providing lower data rates. Three 802.11ad OFDM channels are broken up into 4 smaller channels for a total of 12 channels capable of achieving throughputs of 1.6 Gbps on each channel. This 12-Channel DCN is then simulated over 100 seconds with 1000 application demands and the results are shown in Figure 17. The y-axis starts at 800 completed links to better illustrate the differences between the three simulated DCNs.

![Figure 17: Number of Completed Demands (12-Channel)](image)

The 12-Channel wireless DCN completes 854 demands, only 6 fewer demands than the 10/40 wired DCN. With 12 wireless channels the wireless DCN is able to surpass the conventional 1/10 wired network and approaches the level of performance shown in the 10/40 wired DCN. Furthermore, a breakdown of the number of completed demands on a
per channel basis reveals that only 8 out of the 12 channels are necessary to handle 99.9% of the demands. Only 1 straggling demand is completed in the last 4 channels simulated. The breakdown of completed demands on a per channel basis is shown in Figure 18.

![Figure 18: Number of Completed Demands per Channel (12-Channel)](image)

The 12-Channel wireless DCN is shown to perform on par with its wired ThreeTier equivalent DCNs. This wireless DCN verifies the feasibility of a completely wireless ToR level using 60 GHz wireless links and illustrates the significant energy savings possible. Moreover, the underutilization of the second half of channels gives promise to the ability of the wireless DCN to scale to an increase in number of demands.

## 4.5. Power Consumption

The power consumption of all DCNs is calculated using commercially available data center network switches outlined in section 3.2. The wireless DCN uses a worst case estimation of 1W for the maximum power consumption and 500mW for the typical power consumption. The wireless 60 GHz transceiver power consumption values are based upon the assessment in section 3.2 of emerging 60 GHz transceivers. When simulating multiple channels the transceiver power consumption is multiplied by the number of channels to
represent a worst case scaling in power. The power consumption for all simulated networks is calculated and shown in Figure 19.

![Figure 19: DCN Power Consumption](image)

The wireless DCNs show a 6-8% improvement in the maximum power consumption and a 13-16% improvement in the typical power consumption. The reason each of the wireless DCNs aren’t well below the wired networks is due to the fact that the majority of the DCN’s power consumption derives from the ToR access level switches. These switches are still included in the wireless DCNs because the inter-rack switches all still employ wired links to reach the ToR switch. Only the aggregation and core level switches could be removed in the wireless DCN calculations. A large gap exists between the maximum and typical power consumption values. The primary reason for this difference is that the maximum value is drawn from 100% utilization of every network component at their maximum power levels. While this state of network utilization almost never occurs, data centers have to be able to supply this maximum level to ensure the data center won’t go down. By demonstrating the ability to reduce this maximum power consumption value by roughly 7%, a data center using the proposed wireless DCN could reduce the amount of power infrastructure necessary to meet that peak demand. Furthermore, as ToR access network switches become more power efficient, the wireless DCN proposed will also realize those...
energy savings. All wireless DCNs simulated are shown to provide some amount of energy savings when compared to the wired DCNs.

4.6. Scalability

The scalability of a DCN plays an important role in evaluating how well the network will perform in the future. The ability to handle future workloads and not deteriorate in performance is crucial to be able to extend a data centers overall lifetime. Rather than evaluate the physical scalability of a data center by scaling up the number of racks, a scaling of the application demands is performed. One reason for not scaling the number of racks is because this work investigates the formation of single-hop wireless links. By scaling the physical size of the data center, the 60 GHz wireless transceivers may not always be able to communicate across the entire distance of the data center and would require multi-hop mechanisms to work efficiently. By scaling up the application demands, this work can evaluate the ability of the wireless DCN to handle more demanding workloads. Demonstrating that the wireless DCN performance is similar to the wired networks for only current network data rates and sizes won’t guarantee the wireless DCN will perform as well with future workloads.

4.6.1 Double Data Rate

The application demands are first scaled by doubling the rate at which they generate data. Instead of generating data between 0 and 1 Gbps, the application demands are modified to generate data between 0 and 2 Gbps. The scaling of the data rate is representative of applications that are running on faster hardware and generate data more frequently. The best performing 12-Channel wireless DCN and the two ThreeTier wired DCNs are simulated for 100 seconds with 1000 application demands at twice their normal traffic generation rate. The number of completed demands for each DCN are shown in Figure 20.
The 12-Channel wireless DCN is shown to scale just as well as the 1/10 and 10/40 wired DCNs when the application demand’s data rates are doubled. More demands are able to be completed by each network when the data rate of the demands is doubled because doubling the demand’s data rate reduces the average time to completion for all demands. This allows more demands to be able to be completed within the simulated 100 seconds. The average throughput of the completed demands for each network are shown in Figure 21.
The 12-Channel wireless DCN is able to sustain a higher average data rate when compared with the 1/10 DCN, however the 12-Channel wireless DCN doesn’t perform as well as the 10/40 DCN in terms of throughput. One reason the wireless DCN didn’t perform better than the 10/40 DCN is because the maximum achievable data rate observed for each channel in the 12-Channel DCN is 1.6 Gbps, which falls under the maximum possible 2 Gbps data rate some application demands require. The 10/40 DCN’s links are all always above 2 Gbps.

### 4.6.2 Double Data Size

The application demands are then scaled by doubling only the size of each application demand. The doubling of the data size is representative of applications that require twice as much data to pass through the DCN. The number of completed demands for each DCN with a scaling of the data size are shown in Figure 22.

![Figure 22: Number of Completed Demands (Double Data Size)](image)

When all application demand’s data sizes are doubled, the 12-Channel wireless DCN demonstrates that it can scale as well. Moreover, the wireless DCN is shown to scale better when the data size is doubled than when the data rate is doubled. The average throughput of completed demands for each network are shown in Figure 23.
Only the data sizes are doubled and not the data rates. The average sustainable link data rates for the 10/40 and 12-Channel DCNs fell around the average application demand data rate of roughly 0.5 Gbps. The 1/10 wired DCN is shown to not perform as well when the data rate sizes are scaled.

### 4.6.3 Double Data Rate & Size

Finally, both the data rate and data size of each application demand are doubled. This represents applications that require both faster traffic generation rates and more data to be sent across the network. All three DCNs are simulated with the combination of these two parameters scaled. The number of completed demands for each DCN are shown in Figure 24 and the average data rates for completed demands are shown in Figure 25.
Similar to both individually scaling the data rates and data sizes, the 12-Channel wireless DCN successfully demonstrates the ability to scale with both parameters scaled at the same time. Additionally, the distribution of completed demands across each channel in the 12-Channel wireless DCN is almost identical to the 12-Channel simulation. This indicates that further scaling could be performed with only a minor decrease in the number of completed
demands. The 12-Channel wireless DCN completed only 3 fewer demands than in the 12-Channel simulation with no scaling of the application demands.

4.7. Limitations

The simulated 12-Channel wireless DCN successfully demonstrates the ability to perform at and around its ThreeTier wired DCN equivalents, however a 12-Channel wireless design brings with it certain implementation challenges. Currently a 12-Channel wireless module doesn't physically exist. Such a system would require precise control over center carrier frequencies and their surrounding subcarrier frequencies. Additionally, a multiple input multiple output (MIMO) configuration would most likely be necessary to be able to send multiple data signals using the same ToR transceiver. Furthermore, in the United States the 802.11ad center frequency defined at 64.80 GHz cannot be legally used due to FCC regulations restricting the 60 GHz band to frequencies between 57.05 and 60.00 GHz. Opening up further 60 GHz bandwidth by the FCC above the maximum 60.00 GHz would enable the use of additional bandwidth and the ability to generate more concurrent links on separate channels.

In addition to the challenges brought about by the physical design of the 60 GHz transceivers, the necessary LoS paths above racks within a data center may not always exist. Additional data center infrastructure or building support beams could easily block 60 GHz signals in essentially the same way as the large cabling overheads. In this case, more sophisticated wireless techniques could be employed to circumvent physical obstructions. Multi-hop routing or 3D-beamforming techniques are two methods that could be used to establish non-LoS paths by creating communication paths around physical obstructions.

The geographic size of the wireless DCN also poses a limitation to the ability of the data center to scale out. When more than 160 racks are necessary, additional rows of racks will stretch beyond the maximum distance these wireless DCN ToRs can reliably transmit. This distance limitation could be bypassed by creating multiple islands of wirelessly interconnected racks. These wireless islands can then be linked in a hierarchical fashion.
Another more limited approach would be to generate a novel data center layout to pack more racks into the same physical dimensions of the data center.
Chapter 5

Conclusions

5.1. Concluding Remarks

In this work a wireless DCN architecture is shown to perform as well as a fully wired ThreeTier DCN. The 12-Channel wireless DCN is able outperform the 1/10 wired network in terms of the number of completed demands 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 average power consumption when compared to the wired DCNs. In summary, the wireless DCN architecture is proven to be feasible as a data center network alternative with additional performance and power consumption advantages.

Wireless DCNs alleviate many modern networking challenges, however they are not without their own set of challenges. Further research and investigation is necessary to solve these additional limitations. Nevertheless, wireless 60 GHz DCNs show great promise in replacing burdensome cabling issues and allude to significant performance and energy savings.

5.2. Future Work

This work provides an in depth analysis of one type of wireless data center architecture, however there are many aspects of this approach that require further analysis. One limitation of this investigation is the maximum physical size of the data center. The layout is restricted in order to facilitate one-hop communication between source and destination ToR wireless modules. In order to evaluate larger network sizes, research into wireless 60 GHz multi-hop routing is needed.
To better understand the influence of different types of network traffic on the DCN, additional traffic data sets are needed. A suite of various application workloads for different network sizes would contribute towards a more diverse performance analysis. Data sets of actual network traffic would form a more realistic comparison of how the wireless DCN would perform.

Another area where this work could be extended is the ability to perform dynamic wireless bandwidth allocation to better accommodate network demand requirements. By only providing a fixed amount of bandwidth to each wireless link, some links go underutilized, while others are fully utilized and require additional bandwidth. Providing a dynamic mechanism to the bandwidth allocation of each link may better address the network demands. Further research is required to develop such an approach.

Alternative link establishment mechanisms are another area where this work could improve. The greedy algorithm developed in this work is shown to be a non-optimal approach. Other scheduling algorithms may prove to be better suited to finding the best set of links to establish at any given time. Stochastic approaches may provide a better balance of time complexity and algorithm performance. Additional work is needed to evaluate several link establishment approaches.

The wireless DCN architecture proposed in this work provides a foundation for numerous future works. Wireless DCN architectures bring with them a number of additional design challenges, however the potential benefits in terms of power consumption and performance are promising. This work demonstrates the advantages of one potential DCN architecture and lays the groundwork for future wireless DCN works.
Bibliography


