

# A Survey and Evaluation of Data Center Network Topologies

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**Abstract**—Data centers are becoming increasingly popular for their flexibility and processing capabilities in the modern computing environment. They are managed by a single entity (administrator) and allow dynamic resource provisioning, performance optimization as well as efficient utilization of available resources. Each data center consists of massive compute, network and storage resources connected with physical wires. The large scale nature of data centers requires careful planning of compute, storage, network nodes, interconnection as well as inter-communication for their effective and efficient operations. In this paper, we present a comprehensive survey and taxonomy of network topologies either used in commercial data centers, or proposed by researchers working in this space. We also compare and evaluate some of those topologies using *mininet* as well as *gem5* simulator for different traffic patterns, based on various metrics including throughput, latency and bisection bandwidth.

## 1. Introduction

A data center is a facility used to house computer systems and associated components, such as telecommunications and storage systems [1]. They are key enabler for cloud computing to provide Software-as-a-service (SaaS), Infrastructure-as-a-service (IaaS) for online web services, big data computing, large simulations etc. Today’s data center network (DCN) contains thousands of compute nodes with significant network bandwidth requirements. Companies like Amazon, Google and Microsoft are building large data centers for cloud computing [2] to keep up with application demands. Recent trends show companies like Dropbox, Apple embracing the move to build their own private cloud in order to gain better control, security and higher efficiency [3], [4]. The popularity of cloud, scale of data centers and desire to achieve highest level of application performance requires careful planning of compute, storage and the interconnection network or topology.

While data centers offer tremendous benefits, bandwidth demands are doubling every 12-15 months as shown in Figure 1. A number of recent trends drive this growth. Many data center applications require bandwidth intensive one-to-

one, one-to-several (e.g. distributed file systems [5]), one-to-all (e.g. application data broadcasting), or all-to-all (e.g. MapReduce) [6] communication. Data set sizes are continuing to explode with more photo/video content, logs, and the proliferation of internet-connected sensors. As a result, network intensive data processing pipelines must operate over ever-larger data sets. However, today, deployment of even the highest-end enterprise network equipment only delivers 50% of the available bandwidth. The vital challenges faced by the legacy DCN architecture trigger the need for new DCN architectures, to accommodate the growing demands of the cloud computing paradigm.

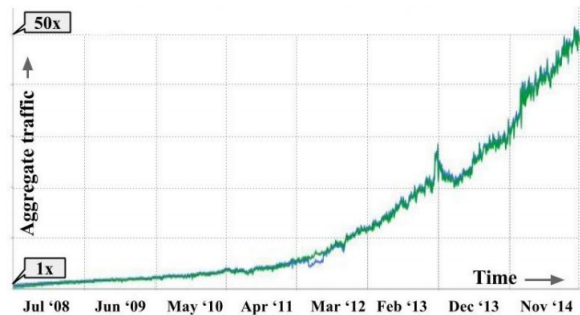


Figure 1: Aggregate server traffic in Google’s Data Centers

In this paper, we present history and taxonomy of various DCN topologies that have been proposed so far and how they have advanced the state-of-the-art technology to overcome aforementioned challenges. The main focus while designing the DCN architecture, has been scalability, cost, latency, extensibility. Further, we have implemented Google Fat Tree [7], Facebook Fat Tree [8] and DCell [9] on two different network simulators - *gem5* [10] and *mininet* [11]. We present our evaluation results and compare latency and throughput metrics for different network traffic patterns. With this work, we hope to present a general overview of various DCN topologies, as well as experimental results to corroborate our analysis.

This paper is organized as follows. Section 2 elaborates on general architecture of data centers along with illustrating

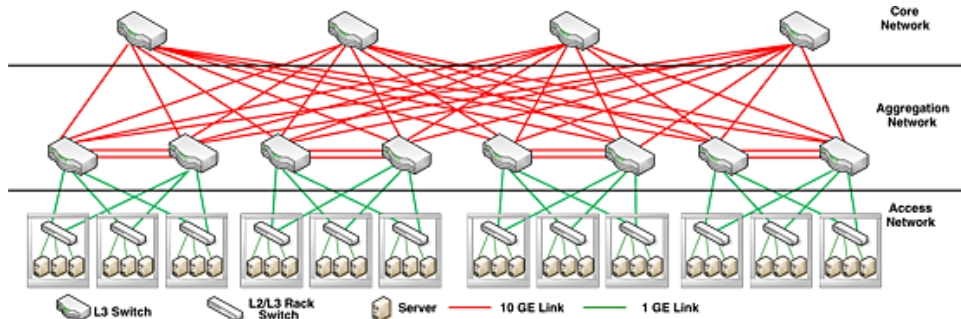


Figure 2: Legacy DCN Architecture

terms that are used frequently in this space. Section 3 explains fundamental differences in topologies for DCN compared to Network on Chip (NoCs). We provide summary of various topologies that have been used in commercial data centers or proposed by researchers in Section 4. Taxonomy of DCN topologies is presented in Section 5. Section 6 presents simulation results from our experiments on both *gem5* and *mininet*. Finally, we discuss our conclusion and future work in Section 7.

## 2. Background

Data Center Networks (DCN) today, are typically based on the three tier, hierarchical, tree based architecture as shown in figure 2. It has a core tier at the root of the tree, an aggregation layer in the middle and edge tier at the leaves of tree. A group of hosts (mostly 16/32) is connected to one switch, called ToR switch (Top of Rack), building the edge (access) layer of the hierarchical tree structure. Core layer and aggregation layer uses high end switches aggregating the traffic coming from the lower layers. Routing is performed by traversing up the tree until the lowest common ancestor and then, down the tree to reach to the final destination. There exists redundant paths among two hosts in the network allowing packet delivery in case of switch failures. Unlike Network on Chip (NoCs), data center hosts and switches implement much more complex protocols to ensure reliability of communication. We discuss some of the most widely used protocol as follows.

### 2.1. Ethernet

Ethernet is a data link layer protocol to send packets (frames) from one point to another point (host or switch), directly connected to each other. It provides best effort service based on collision detection (CD) without any flow control. Frames are dropped if the queues are full at the receiver without notifying the sender. Further, Ethernet switches are similar to a NoC crossbar and implement FIFO model for packet processing.

### 2.2. TCP/IP

IP is a network layer protocol to ensure routing of packets from one host to any other host in the network.

TCP runs on top of IP layer and implements: (a) flow control to prevent receiver’s buffer from overflowing, (b) retransmission to ensure reliable data transfer, and (c) congestion control to minimize packet loss. Note that data centers, therefore, only implement end to end flow control and there is no mechanism to ensure point to point (i.e. link level) packet delivery as Ethernet only provides best effort service.

### 2.3. Over-subscription

Many data center designs introduce over-subscription as a means to lower the total cost of the design. We define the term over-subscription to be the ratio of the worst-case achievable aggregate bandwidth among the end hosts to the total bisection bandwidth of a particular communication topology. An over-subscription of 1:1 indicates that all hosts may potentially communicate with arbitrary other hosts at the full bandwidth of their network interface. An over-subscription value of 5:1 means that only 20% of available host bandwidth is available for some communication patterns. Although data centers with over-subscription of 1:1 are possible, the cost for such designs is typically prohibitive, even for modest-size data centers [7].

## 3. Comparison with NoCs

Data Center Network topologies are inspired from the world of Network on Chip (NoC). However, there are some key differences. We highlight some of them as below -

- **High Radix Routers:** Data centers typically employ high radix routers in order to utilize more path diversity to achieve higher throughput. The number of links is not a concern in comparison to on chip networks, as space is an inexpensive commodity.
- **Link Bandwidths:** In off chip networks, the bandwidth available usually differ among links belonging to different levels (tiers) in the hierarchy. This allows the number of downlinks at a router to exceed the number of uplinks. Hence, to equalize total incoming and outgoing bandwidth, link capacity is usually seen to increase as we go up the hierarchy.
- **Routing Algorithms:** NoCs commonly tend to be two/three dimensional and hence, adopt dimensional

routing such as XY routing, turn model based routing. Whereas, off chip networks tend to use algorithms such as ECMP (Equal Cost Multipath Routing) to make use of redundant paths in the network.

- **Flow Control:** Off chips networks do not perform any kind of link level flow control unlike NoCs as discussed in section 2. A packet may get dropped when output buffers are full.
- **Routing delay and Link Latency:** Both routing delay and link latency tend to be typically higher in off chip networks, merely due to much larger size of the components. That is why, diameter for off chip topology is typically smaller compared to NoCs.

## 4. History of Data Center Networks

In this section, we describe some of the data center network (DCN) topologies that have been proposed over the time. We have organized all of these topologies on a timeline based on when the corresponding paper was published, as shown in figure 3.

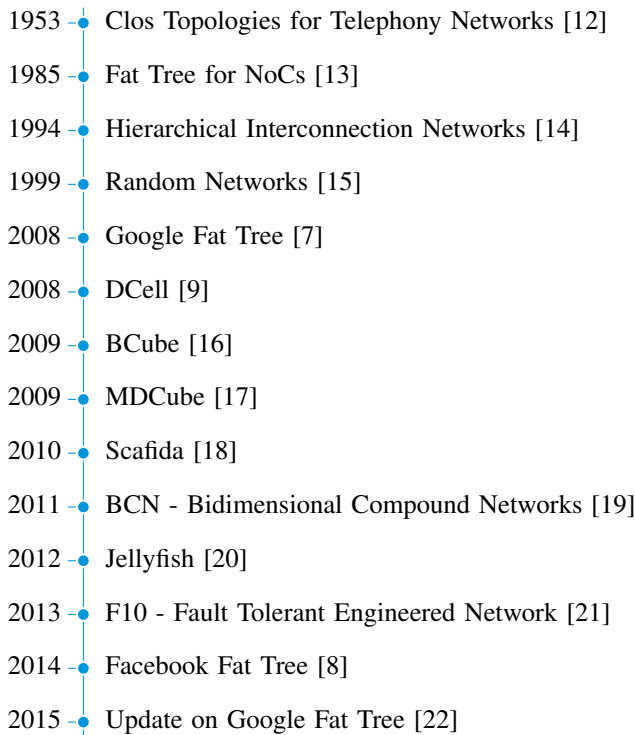


Figure 3: Timeline of DCN Topologies

### 4.1. Fat Tree Topology

More than 50 years ago, Charles Clos proposed non-blocking *Clos* network topologies for telephone circuits [12] that delivers high bandwidth. Many of the commercial data center networks adopt a special instance of *clos* topologies called Fat Tree [13]. FT was originally proposed for on

chip networks (NoCs) organizing processors in a complete binary tree as show in Figure 4. Each Processor is connected to one router (switching node) with a duplex link (two channels/links - one uplink and other downlink). Packet routing is also highly simplified and requires only  $2 \log(n)$  space for destination. Any node can be reached from any other node by traversing a unique path through the common ancestor. Fat Tree topologies are popular for their non-blocking nature, providing many redundant paths between any 2 hosts. Such topologies are later used to build fast and efficient super computers such as BlackWidow [23] along with successful use in commercial data centers [7], [8].

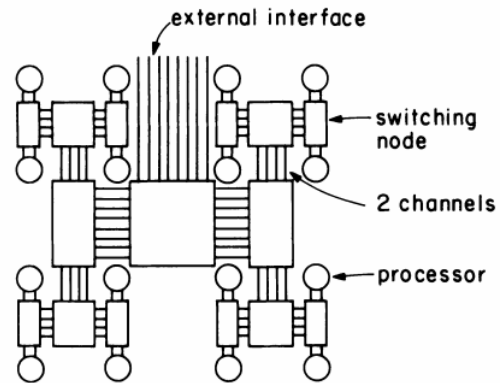


Figure 4: Fat Tree for NoCs (taken from [13])

### 4.2. Google Fat Tree

Google implemented a slight modification of Fat Tree topology to interconnect commodity Ethernet switches in order to produce scalable large data centers [7]. The topology consists of  $k$ -port routers along with commodity compute nodes at the leaves of the tree as shown in figure 5. The basic building block of the data center is called a pod. A Fat Tree consists of  $k$  pods, each containing two layers of  $k/2$  switches. Each  $k$ -port switch in the lower layer is directly connected to  $k/2$  hosts. Each of the remaining  $k/2$  ports is connected to  $k/2$  of the  $k$  ports in the aggregation layer of the hierarchy. There are  $(k/2)^2$   $k$ -port core switches. Each core switch has one port connected to each of the  $k$  pods.

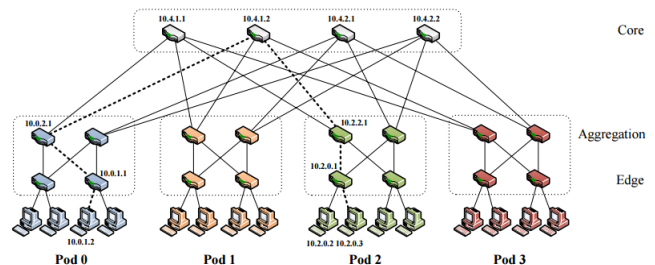


Figure 5: Google Fat Tree Topology (taken from [7])

Routing in Fat Tree is implemented as follows. Each flowlet takes a unique path out of all possible paths to reach

the common ancestor while avoiding reordering of packets. A flowlet is a collection of TCP segments (packets) sent in a quick succession. After reaching the common ancestor, it traverses downwards taking the only possible path. This design allows to build the data centers using commodity switches instead of very expensive routers reducing the overall cost significantly. It can use all the available redundant paths to send packets between two nodes while also benefiting from adaptive routing.

### 4.3. DCell

DCell is a server-centric hybrid DCN architecture where one server is directly connected to many other servers [9]. A server in a DCell is equipped with multiple Network interface cards (NICs). The DCell follows a recursively build hierarchy of cells as shown in Figure 6. A cell0 is the basic unit and building block of DCell topology arranged in multiple levels, where a higher level cell contains multiple lower layer cells. A cell0 contains  $n$  servers and one commodity network switch. The network switch is only used to connect the server within a cell0. A cell1 contains  $k = n + 1$  cell0 cells, and similarly a cell2 contains  $k * n + 1$  cell1. A Dcell can be built recursively resulting in more than 3.26 million servers with an average diameter of less than 10 ( $k=3, n=6$ ). Routing in Dcell follows a divide and conquer approach. For packets to reach from a source host to destination host, it needs to traverse from source to common ancestor DCell, a link connecting the previous level DCells and finally, to the destination. The exact path can be found similarly in a recursive fashion. The protocol is further extended to implement fault tolerant routing (DFR) to cope with link or node failures. Overall, DCell is highly scalable and fault tolerant topology however, it provides low bisection bandwidth.

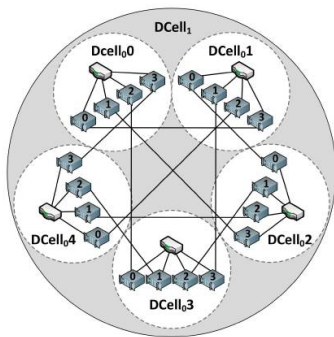


Figure 6: DCell1 network when  $n=4$ , composed of 5 DCell0, forming a fully connected graph. (taken from [9])

### 4.4. BCube

BCube network architecture takes a server-centric approach to produce a modular data center (MDC) using commodity switches. It places intelligence on MDC servers

and works with low end COTS mini switches. There are two types of devices in BCube: servers with multiple ports and switches that connect to a constant number of servers. It is recursively defined structure with  $BCube_0$  simply being  $n$  servers connected to an  $n$ -port switch.  $BCube_k$  is constructed with  $n$   $BCube_{k-1}$  having  $n^k - 1$  switches each connecting same index server from all the  $BCube_{k-1}$ . With 8-port mini-switches, it can support up to 4096 servers in one  $BCube_3$ . The figure 7 shows a  $BCube_1$  with  $n=4$  with 2 levels. Source based routing is performed using intermediate nodes as packet forwarder ensuring, decreasing hamming distance between each consecutive intermediate host to the destination. Periodic search for optimal path is performed in order to cope with failures in the network. One-to-all, all-to-one and all-to-all traffic can also be routed by using redundant  $(k+1)$  ports at each hosts.

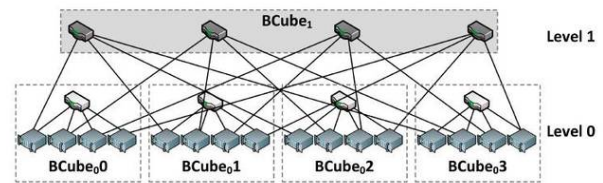


Figure 7: BCube Topology (taken from [16])

### 4.5. MDCube

In order to build a large data center, MDCube [17] uses BCube [16] as its building block and allows to interconnect hundreds and thousands of BCube containers in 1-D or 2-D fashion to achieve high network capacity as shown in figure 8. It connects two containers in the same dimension (i.e. row or column) with a direct link to form a basic complete graph among all containers similar to a Flattened Butterfly. Single path routing is performed topology by finding a pair of switches in an intermediate container.

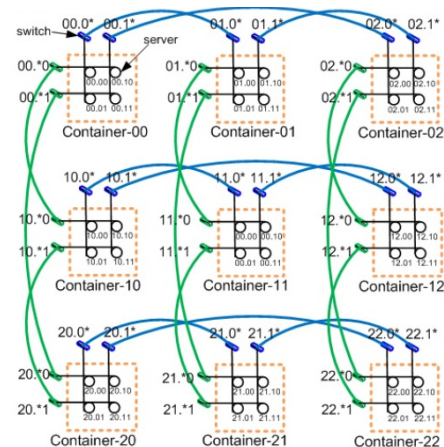


Figure 8: A 2-D MDCube Topology constructed from  $9=3*3$   $BCube_1$  containers with  $n=2, k=1$  (taken from [17])

## 4.6. Scafida

Scafida [18] is a asymmetric scale-free data center network topology to achieve short distance, high error tolerance and incremental build. Scale-free networks have two important properties - small diameter and high resistance to random failures. The same set of properties are highly desirable in data center network topologies. Scafida provides methodologies to construct such a topology for data centers while making reasonable modifications to original scale-free network paradigm [15]. Scafida consists of heterogeneous set of switches and hosts in terms number of ports/links/interfaces. The topology is built incrementally by adding a node and then, randomly connecting all the available ports to existing empty ports. The number of ports are limited by the available ports on a node unlike original scale-free networks. Such a network provides high fault tolerance. Results show that even if 20% of the switches fail, more than 90% of the server pairs still have 2 disjoint paths. Examples of a scale-free topology is shown in figure 9. No routing algorithm is proposed yet for such networks though, the idea of random construction of a data center looks promising. However, wiring, handling failure of nodes with large degree, routing algorithm are still major issues that needs to be addressed.

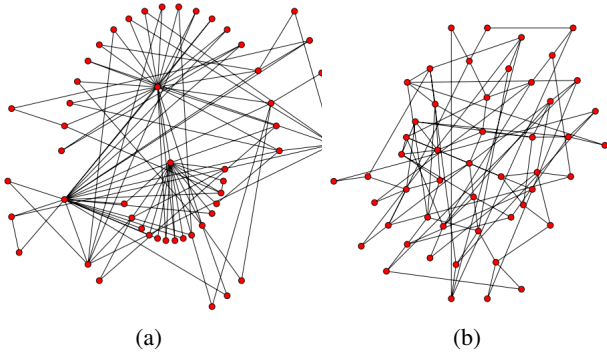


Figure 9: (a) Scale Free Network (SFN), (b) SFN with maximal degree 5 (taken from [18])

## 4.7. HCN & BCN

Hierarchical Irregular Compound Network (HCN) and Bidimensional Compound Network (BCN) [19] are dual-port-server based, symmetric, regular and extensible architectures. HCN is recursively defined structure.  $HCN(n, 0)$  is the base case, consisting of  $n$  dual port servers, each of them connected to  $n$  port switch on one of the two ports. Each of the server will have 1 port free, resulting in  $n$  total free ports in  $HCN(n, 0)$ . A  $HCN(n, 1)$  is then, constructed using  $n$   $HCN(n, 0)$  modules by connecting  $(n - 1)$  out of  $n$  available ports of each  $HCN(n, 0)$  with rest of the  $(n - 1)$   $HCN(n, 0)$ . Each of the  $HCN(n, 0)$  module will have 1 port left free and allowing a further extension using total of  $n$  free ports in  $HCN(n, 1)$ . In general, a high-level  $HCN(n, h)$  employs  $n$  modules of  $HCN(n, h - 1)$

consisting of  $n$  free ports for further extending the topology. An example of  $HCN(4, 2)$  is shown in figure 10.

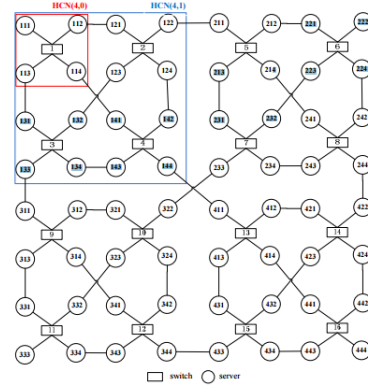


Figure 10: HCN( $n=4, h=2$ ) (taken from [19])

BCN is multi-level irregular compound graph recursively defined in the first dimension, and a level one regular compound graph in the second dimension.  $BCN(\alpha, \beta, 0)$  has  $(n = \alpha + \beta)$  where only  $\alpha$  ports are available for further extension similar to HCN. These  $\alpha$  servers having the  $\alpha$  ports available are called master servers. In the second dimension, it is a closed structure (i.e. cannot be extended further) and constructs a fully connected graph of  $BCN(\alpha, \beta, h)$  modules on the available  $\alpha^h \cdot \beta$  servers, called slave servers. This provides flexibility in extensibility of the topology as necessary by controlling the parameters  $\alpha$  and  $\beta$ . Routing in BCN is performed similar by recursively finding an intermediate link that interconnects the two BCN modules where source and destination are located.

## 4.8. Jellyfish

Jellyfish is a flexibility and high bandwidth oriented network topology consisting of  $n$  port switches. Each switch has  $r$  ports connected to other switches and rest of the  $k = (n - r)$  ports connected to hosts. The links are added by randomly connecting a pair of switches that are not already connected (i.e. not neighbors) and having at least one free port. The topology can be further extended by removing existing  $(x, y)$  link and adding  $(x, p_1)$  and  $(x, p_2)$  link where  $p_1, p_2$  are free ports on the new switch. Such random graphs have higher throughput because they have low average path lengths in comparison to symmetric topologies such as fat tree. However, routing, packaging issues needs to be addressed for practical use of the topology.

## 4.9. F10 (Fault Tolerant Engineered Network)

F10 [21] is a simple modification to Fat Tree topology to gain better fault tolerance properties. The key weakness in the standard Fat Tree is that all sub-trees at level  $i$  are wired to the parents at level  $i + 1$  in an identical fashion. A parent attempting to detour around a failed child must use roundabout paths (with inflation of at least four hops)

because all paths from its rest of the children to the target sub-tree use the same failed node. The AB FatTree in F10 solves this problem by defining two types of sub-trees (called type A and type B) that are wired to their parents in two different ways as show in figure 11. With this simple change, a parent with a failed child in a type A sub-tree can detour to that sub-tree in two hops through the parents of a child in a type B sub-tree (and vice versa), because those parents do not rely on the failed node.

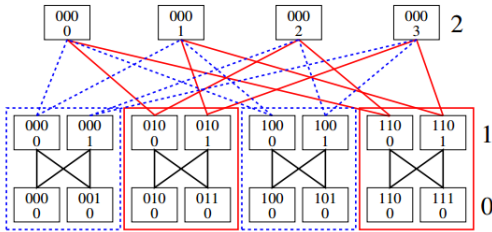


Figure 11: F10 Topology, blue links are part of A sub-tree, red links are part of B sub-tree (taken from [21])

#### 4.10. Facebook Fat Tree

Facebook deployed a version of Fat Tree topology in order to achieve high bisection bandwidth, rapid network deployment and performance scalability to keep up with the agile nature of applications running in the data centers. It consists of pods, a standard unit of network as show in figure 12. The uplink bandwidth of each TOR is 4 times ( $4 \times 40G = 16 \times 10G$ ) the downlink bandwidth for each server connected to it. To implement building-wide connectivity, it created four independent "planes" of spine switches [Tier 3 switch], each scalable up to 48 independent devices within a plane. Border Gateway Protocol (BGP4) is used as a control protocol for routing whereas a centralized controller is deployed to be able to override any routing paths whenever required, taking a "distributed control, centralized override" approach. In order to use all the available paths between 2 hosts, ECMP (Equal Cost Multiple Path) routing with flow based hashing is implemented.

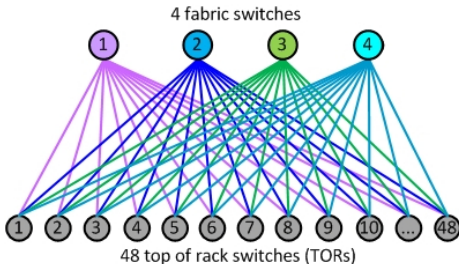


Figure 12: Facebook Fat Tree Topology (taken from [8])

### 5. Taxonomy of DCN Topologies

In this section, we present taxonomy of the DCN topologies that we have discussed so far. We believe that following

criterion are subset of degrees of freedom that are available to a data center network architecture while designing a new topology or choosing from existing topologies.

#### 5.1. Build Approach

Data centers can be built either by adding links between 2 nodes randomly or in deterministic pattern (see Table 1). Random topologies have lower diameter but suffer from complex routing algorithms and wiring issues.

Build Approach	Description	Examples
Random	Add links between nodes using a randomized algorithm	Scafida, Jellyfish
Deterministic	Add links between nodes in a deterministic pattern	Fat Tree, DCell, BCN, BCube

TABLE 1: DCN Topologies based on build approach

#### 5.2. Server-Centric v/s Switch-Centric

Some DCN topologies have hosts that take part in routing and forwarding of packets. It requires them to have additional logic of forwarding and routing traffic. Software routing may have degraded performance and can affect the applications running on the hosts.

	Description	Examples
Server-Centric	Both routers and hosts forward traffic	DCell, MDCube, Scafida, BCN
Switch-Centric	Only routers forward traffic	Fat Tree, Jellyfish

TABLE 2: Server v/s Switch Centric DCN Topologies

#### 5.3. Direct v/s Indirect

	Description	Examples
Direct	All routers have host(s) attached to them	DCell, MDCube, Scafida, BCN
Indirect	Routers may not have host(s) attached to them	Fat Tree

TABLE 3: Direct v/s Indirect DCN Topologies

#### 5.4. Symmetric v/s Asymmetric

Symmetric DCN architectures allow uniform packaging and simplified wiring of the topology. Examples of symmetric topologies are Fat Tree, MDCube, HCN whereas DCell, Scafida and Jellyfish are asymmetric architectures. Note that deterministic topologies may not necessarily be symmetric such as DCell.

#### 5.5. Extensibility

HCN, BCN, Scafida, Jellyfish are a few examples of extensible DCN architectures. The size of these topologies can be easily increased without any upper limit. However, size of Fat Tree and DCell topologies is limited due to limited number of available ports on the switches.

## 5.6. Deployment Methodology

Data centers are built using switches and hosts. A modular data center system is a portable method of deploying data center capacity.

Deployment Methodology	Description	Examples
<b>Modular</b>	Portable building block (shipping container)	BCube, MDCube
<b>Non-Modular</b>	Switch and host (native)	Fat Tree, DCell, Jellyfish, Scafa

TABLE 4: Topologies based on deployment methodology

## 5.7. Over-subscription

Typically, DCN topologies are over-subscribed in order to reduce the total cost of design as discussed in section 2.

Over-subscription	Description	Examples
<b>Non-blocking</b>	no over-subscription (over-subscription = 1)	Fat Tree
<b>Blocking</b>	over-subscription < 1	DCell, MDCube, BCN, Scafa, Jellyfish

TABLE 5: Over-subscription based DCN Topologies

## 5.8. Number of Tiers (Levels)

DCN architectures may be defined recursively in which case, the number of levels are not preset and increases as the size of topology increases. Further details are available in Table 6.

Number of Tiers	Description	Examples
<b>Flat</b>	Only single tier topology	Scafa, Jellyfish
<b>Fixed</b>	Predefined number of tiers	Fat Tree
<b>n-tier</b>	Number of tiers vary as size of topology increases	DCell, BCN, MDCube

TABLE 6: Number of Tiers based DCN Topologies

## 6. Evaluation

In this section, we present an experimental comparison of Google Fat Tree, Facebook and DCell topologies using *gem5* and *mininet*.

### 6.1. Topologies Evaluated

**Google Fat Tree.** We implement the Google Fat Tree Topology for ( $k = 4$ ). It consists of 8 servers (hosts) and 20 routers (switches) as follows: 4 core, 8 aggregate, 8 edge switches. Each edge switch could support multiple hosts for further testing. The limiting factor for this topology is the network diameter which is greater than rest of the topologies

**DCell.** We implement 5 cell, 2 levels DCell topology for evaluation purposes. Each cell has 4 hosts and an edge switch to connect to the servers (hosts). In case of mininet, linux hosts have trouble forwarding packets as they see each interface on the same network (broadcast domain). An additional switch, therefore, was added as the edge switch to ensure that the hosts could reach every destination. In order to test all of the links in the topology simultaneously, we place four hosts in each cell with a total of five cells. The limiting factor for the DCell topology is the single edge switch in each cell. The single edge switch creates a bottleneck in the cell limiting the performance of the topology.

**Facebook Fat Tree.** We implement a smaller version of Facebook data center. The smaller version has 48 edge routers and 4 aggregate routers. The limiting factor for the Facebook design is the bottleneck created by connecting 48 edge routers to the 4 aggregate routers. When a 48 port switch or router has all of the connections to other switches that have servers attached then it will be tough for that switch to process packets as fast as they arrive. Theoretically, the saturation throughput for a switch or routers with  $N$  ports as  $N$  approaches infinity is  $2 - \sqrt{2}$  or around 58.6%.

### 6.2. Traffic Patterns

We have evaluated the above topologies with a subset of following traffic patterns -

- **Uniform Random Traffic:** Each packet is sent to any other node with equal probability.
- **Bit Complement Traffic:** Each node exchanges packets with a node on the opposite side of the network. To compute the destination address, a bit wise inversion is carried out of the source coordinates. This traffic provides a well balanced traffic across the network.
- **Bit Reverse Traffic:** A message originating from a host having host address as  $B_1B_2 \dots B_n$  is destined for a host with the address  $B_nB_{n-1} \dots B_1$ .
- **Tornado Traffic:** Each node  $i$  sends traffic to  $(i + \frac{N-1}{2}) \bmod N$  where  $N$  is total number of hosts.

### 6.3. Mininet

For evaluation, we used Mininet as our network emulator and POX as the OpenFlow controller. The exact code can be found at <https://github.com/lebednik/ICNmininet>. Mininet was chosen because of the ease of use with Python. POX was chosen because it provided the best network convergence rates among the OpenFlow controllers tested (RIPL-POX, OpenDaylight, and Floodlight).

Originally, we began programming the topologies with routers instead of switches but with even a scaled version of the Google Fat Tree topology there are forty networks or broadcast domains. Thus, for each router (programmed as its own class of host in Mininet), forty commands (network

address and next hop) would need to be entered before the router knows about every destination in the network. Similarly, for DCell and Facebook topologies, the routers would need to know about 35 and 240 networks respectively.

Tests were performed with *iperf* and *ping*. The *iperf* command can calculate the bandwidth available between any two hosts by creating a client-server Transmission Control Protocol (TCP) connection. The *ping* command can not only provide connectivity results in the network but can also be used for latency measures. *ping* also provides the capability to determine the size of the packet that you are sending on the network which allows sending larger packets to emulate sending larger files. All tests were run on a dedicated 64-bit Ubuntu server with 8 vCPUs and 15 GB memory.

**Bisection Bandwidth Testing.** To test the bisection bandwidth, the team used *iperf* to create Transmission Control Protocol (TCP) connections between bit complement hosts. The *iperf* command provides a variable time connection between two end devices, one will act as the host and the other the server. The command provides a readout of the client to server connection in bits per second (bps). Since *iperf* acts as a client to server connection, the test would designate one side as the client side and the other as the server side and then switch the sides to pass as much data across the bisection as possible. Each test was then averaged and then provided a percentage of the total bisection bandwidth to normalize the data.

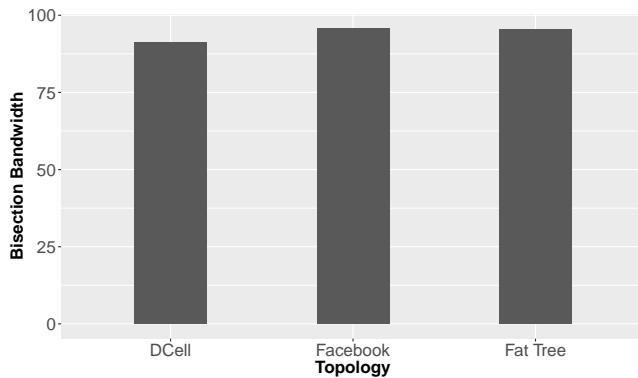


Figure 13: Percentage of Bisection Bandwidth Achieved

Figure 13 shows that the Google Fat Tree topology slightly outperforms the Facebook topology. The test was run several times and the Google and Facebook topology continually showed performance in the 95% range on all links. The DCell Topology provided around 95% utilization on most links but with the bottleneck (many connections to the same router) close to the hosts, one link would show around 78% total utilization dropping the average utilization greatly. Since DCell is using an edge switch or the multi-homed (multiple connections to the same host) server, this result would make sense as the server would have greater difficulty multiplexing on all of the links simultaneously while an edge switch would create a bottleneck in the network.

**Packet Size Testing.** The Maximum Transmission Unit (MTU) is the largest packet allowed on the network links. Based off old Ethernet standards, the largest packet allowed on the network is 1500 bytes. Routers and hosts drop anything larger to prevent "Ping of Death" attacks and to maintain the standard. For comparison, the normal ping packet size is 82 bytes. Network designers would know the average packet size that they would want to design for their networks. For example, moving large amounts of data within a data center would require lower latency with larger packets. The design would need to prevent bottlenecks. Whereas a network that has a smaller average packet size could have potential bottlenecks as long as the link speeds were fast enough.

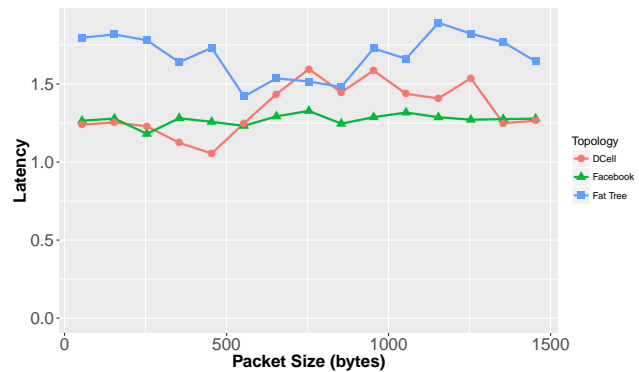


Figure 14: Average Latency (ms) vs Packet Size(bytes)

Figure 14 shows the average latency of each of the networks versus the size of the packet placed on the network. As expected the Facebook topology provides the lowest latency in the network because of the diameter of the network. The DCell topology begins to bottleneck when the size of the packet increases over 200 bytes. The DCell Topology still provides less latency. The Facebook topology displays the lowest latency despite the size of the network and the potential for bottlenecks. The Facebook topology has a shorter overall diameter but the aggregation of 48 edge routers with hosts to four aggregate routers has the potential for a large bottleneck when compared with the Google Fat Tree which has equal links between all of the devices in the topology.

**Network Saturation Testing.** To test the networks during periods of high utilization, hosts pinged their bit complement with a maximum packet size for a three times as long as the other tests. The purpose of this was two-fold. First, it would provide a greater amount of time for the network to reach saturation, much like test in NoCs perform. Second, the team wanted to test the bisection capacity with the largest packets sizes available on the network.

Figure 15 shows the average latency for packets sent in over the course of the 30 second test. The DCell topology slightly outperforms the Facebook topology by less than a tenth of a millisecond. Based on the diameter of the network and the hops each packet would take, Facebook



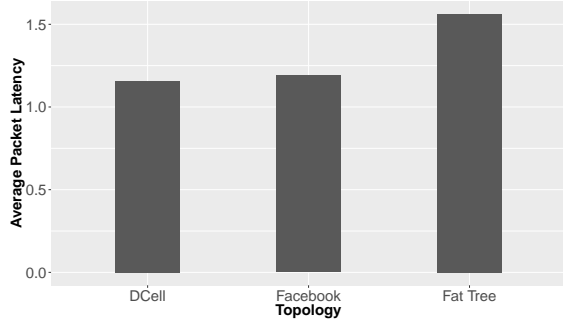


Figure 15: Latency Test for 30 seconds at MTU(ms)

should outperform DCell. This test could show that Facebook reaches its saturation and starts under-performing due to the bottleneck at the core level. The bottleneck of the Facebook topology is much bigger than the bottleneck of the DCell with an average of 12 connections from the edge level to the aggregate level. Whereas, DCell has 4 hosts connected to one router at the edge level. The diameter of the Google Fat Tree topology causes the higher latency in the network. Based off these results, the topology diameter has a significant impact on the latency but so does any bottlenecks in the network.

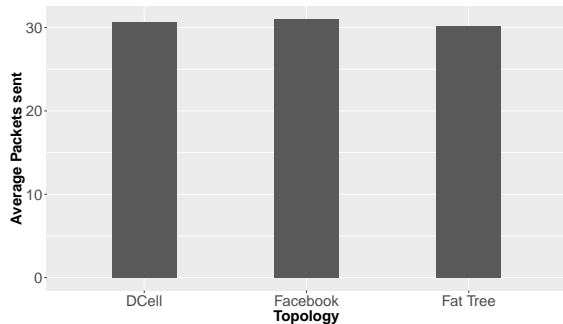


Figure 16: Packets Sent During Stress Test per host

Overall, during the stress test, each host was able to send over 30 packets apiece successfully. Figure 16 provides the average number of packets sent by each host in each topology. The Facebook hosts sent almost one packet more per host during the period than the Google Fat Tree. So in comparison, the Facebook topology was able to send 48 more packets or 72KB with the 10 Mbps links.

**Scalability Testing.** To further evaluate the network performance for each of the topologies, the team began adding more hosts to the edge switches. This scalability testing is important as it helps to determine the optimal number of servers that the data center engineer would want to place under each edge switch.

As shown in Figure 17, each topology provides less latency at different amounts of hosts. The team ran the simulations several times at each of the points and obtained similar results. Although at the bases state Fat Tree has

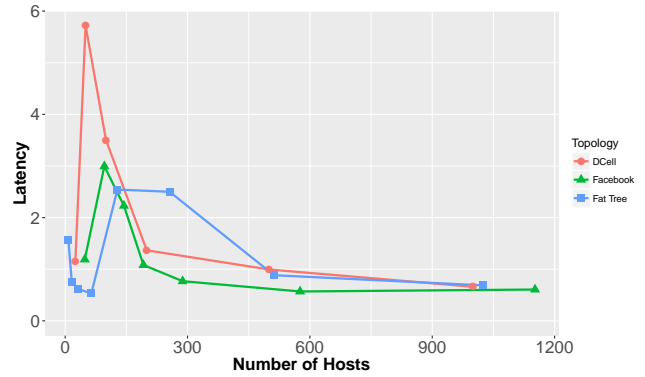


Figure 17: Traffic Latency versus number of hosts(ms)

greater latency, by the time that there are a similar amount of hosts on the network, Google Fat Tree has less latency than the Facebook topology. All of the topologies have an interesting peak latency in the 50 to 300 host range but then level off towards an equilibrium. The Facebook topology outperforms all others from 144 hosts onward.

#### 6.4. Evaluation Using *gem5*

*gem5* [10] is a simulation platform for computer-system architecture research. It came as a merger of the *m5* simulator [24] from the University of Michigan Ann Arbor and the *GEMS* simulator [25] from the University of Wisconsin Madison. *gem5* uses *garnet* to simulate the interconnection network for NoCs. We modeled Google Fat Tree and DCell topology on Garnet network simulator [26] by modifying it to emulate the working of an actual off chip network, as closely as possible.

First, the router delay is increased to five cycles by increasing the number of stages in the router pipeline. The link latency was increased to 10 cycles to model higher link propagation latency. We used table based routing, which is already available in Garnet. We further modified the algorithm to choose one of the redundant paths randomly. For example, in Google Fat Tree topology, a packet has more than one possible path while going up the tree. However, once the packet reaches the core router, it has only one available path going down the tree. We choose a path randomly while going up the tree to achieve higher link utilization. An important difference is that off chip networks have a much higher number of queues than on chip networks, and so we simulate that by having number of virtual channels as equal to 100. We also consider one flit per packet, to simplify our assumptions. In this work, We attempt to implement dropping of packets as is done commonly in data center networks. Packets are randomly dropped and re transmitted by the sender if an available outgoing queue is not available. We plan to compare the results of this implementation with having the packets wait for their turn, to see latency benefit in each, as the future work of this project. We ran several simulations on Google Fat Tree topology and Microsoft's

DCell topology, the results of which have been discussed below.

**Google Fat Tree: Throughput across different traffic patterns:** . Figure 18 shows the values of packet reception rate (total\_packets\_received/num-cpus/sim-cycles) at different injection rates for four different traffic patterns - uniform random, bit reverse, bit complement, and tornado. It can be seen in this figure that, almost all traffic patterns except tornado show similar reception rate. The reason for this is, in the Google Fat Tree topology, if the destination host is outside of the pod belonging to the source, it will take the same number of hops, for all cases, except tornado. Hence, all patterns present results similar to that of uniform random pattern. However, in the case of tornado, we see a much better reception rate for the reason being that due to nature of tornado traffic, it is possible that some of the source and destination pairs are within the same pod, which results in a much higher reception rate.

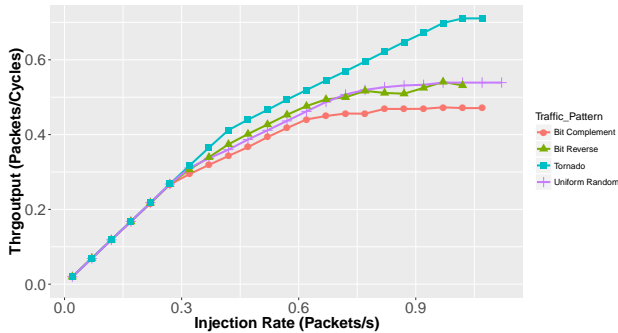


Figure 18: Google Fat Tree: Throughput across different traffic patterns

**Google Fat Tree: Packet Reception Rate for different number of virtual channels:**. Figure 19 shows the packet reception rate for Google Fat tree topology across three different number of virtual channels - 20, 50 and 100. The packet reception rate does not necessarily get better with more number of virtual channels, the reason for this being, there is no contention delay to begin with, due to having multiple number of VCs.

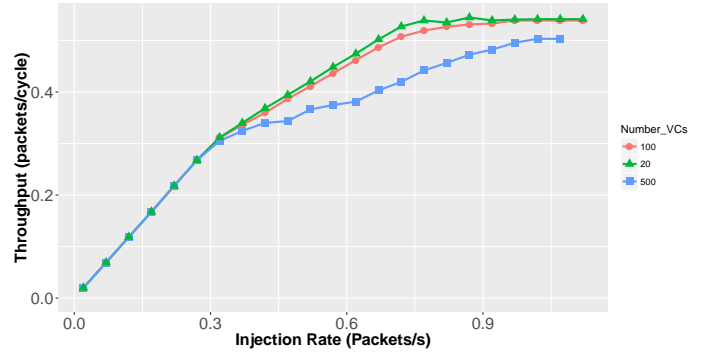


Figure 19: Google Fat Tree: Packet Reception Rate for different number of virtual channels

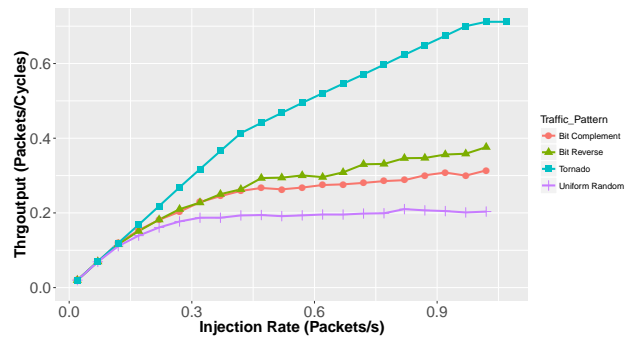


Figure 20: DCell: Throughput across different traffic patterns

number of links to number of hosts. DCell essentially has one switch per module, no matter how many servers are there per module, and so that causes a bottleneck in DCell performance.

**DCell: Throughput across different traffic patterns:**. Figure 20 shows the throughput values obtained for DCell topology over four different traffic patterns. Again, Tornado shows much better throughput as compared to other traffic patterns. The reason for this is that tornado traffic pattern does a much better job of distributing the traffic among the links in the network, whereas the other traffic patterns, tend to strain few links more than other.

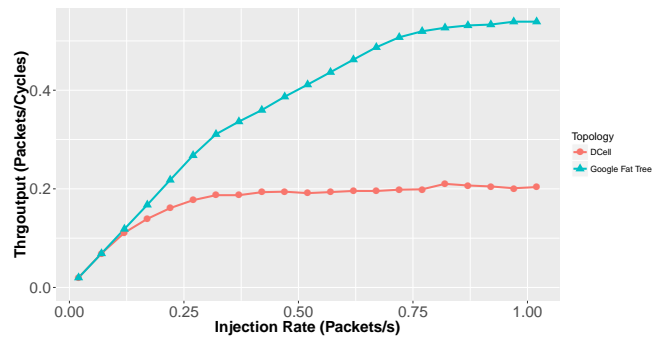


Figure 21: Throughput Comparison of Google Fat Tree and DCell

**Throughput Comparison of Google Fat Tree and DCell.** Figure 21 shows the throughput values of Google topology to be much higher than that of DCell. This is as expected because the Google topology has a much higher ratio of

**Throughput Comparison of DCell for 20 hosts and 42 hosts.** Figure 22 shows throughput values for two different values of n. For n=4, the number of hosts are 20, and for n=6, the number of hosts are 42. We simulate the throughput for both topologies across two different traffic patterns - uniform random, and bit complement traffic. The

saturation throughput reduces, as we increase number of hosts, because, as discussed above, the number of servers per module switch increases, essentially overloading the switch. This results in a lower throughput as we increase number of hosts. This result is consistent with the conclusion that DCell is essentially a recursive topology, which scales by increasing the number of levels in the topology, as opposed to increasing the number of servers within one level. This results serves to prove this fact.

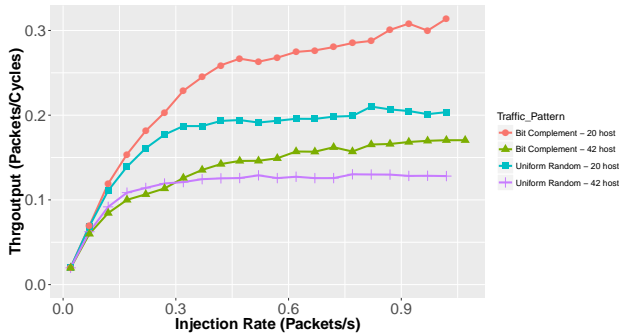


Figure 22: Throughput Comparison of DCell for 20 hosts and 42 hosts

**DCell: Latency comparison across various different traffic patterns.** Figure 23 shows the latency comparison between different traffic patterns of DCell. As discussed in the throughput comparison, tornado better distributes the traffic across the network, and hence, presents better latency than the other traffic patterns.

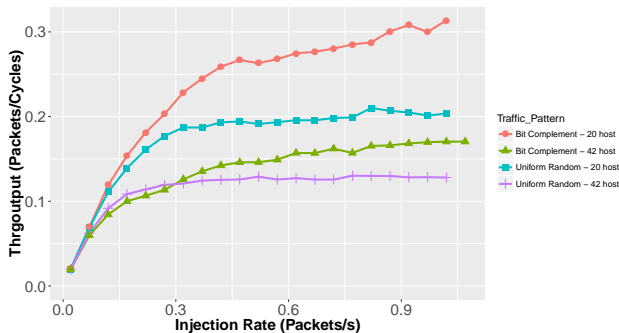


Figure 23: DCell: Latency comparison across various different traffic patterns

## 7. Conclusion & Future Work

By testing the Google Fat Tree and DCell topologies in both gem5 and Mininet, we were able to produce similar results. This helps to verify the results of testing multiple topologies. Both testing in Mininet and gem5 showed that the Google Fat Tree topology outperforms the DCell topology in throughput.

While our research produced some interesting results in regards to the topologies, there is certainly more work to

be done. For our Mininet simulations, we would like to build a controller that is not only able to function with network loops but also provides load balancing. Currently, only the controllers used in production environments, such as Google, are able to control networks with loops and provide load balancing. Most other controllers that work with loops simply use the Spanning Tree Protocol to shut off links that may be redundant.

Implementing the off-chip topologies in gem5 simulator, gave us a lot of insight into the working of the interconnection network in an off chip topology. We have successfully implemented and simulated several of the parameters of data center networks, on garnet. The next steps with regards to implementation in garnet, could be the consideration of scalability of DCN as well as the implementation of packet dropping in garnet, which is a common phenomenon in data center topologies.

During the scaling of hosts testing, Mininet provided interesting results. The team has not previously seen Mininet topologies with such large amount of hosts. Further investigation is required to understand why latency in the network increase drastically for up to 300 hosts and then decreases. The results from the Amazon EC2 server were consistent even when the tests were run several times. While Facebook provided the best overall latency, there are several instances where the other topologies outperform it in regards to the same or approximately the same number of hosts.

There are other traffic patterns that other studies have used to evaluate their designs. In one of the papers, the authors used Stride traffic patterns to mimic their datacenter traffic. This would be another good comparison for the datacenter topologies. We used bit complement for most of the tests in Mininet because it had the same hop count as it would have with the unaltered datacenter.

We have presented a comprehensive survey and taxonomy of Data Center Network topologies that have been proposed in the history of off chip networks. Even though a significant number of topologies have been explored, only a few such as Fat Tree, BCube have been implemented in practice in order to achieve high bisection bandwidth. Today, the principle bottleneck in large scale cluster is often inter-node communication bandwidth. To keep up with this demand, we need scalable network topologies that can fulfill significantly high bandwidth requirements while keeping the cost low.

We have also presented a comparison of a few data center topologies using *mininet* and *Gem5* simulator. We plan to complete our analysis as part of (short term) as part of our future work.

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the reviewers of our paper the provided us with several good points on where to continue our testing and improve our paper. Specifically, one reviewer asked for more information on how to we were going to conduct our testing in Mininet. Prof Krishna also asked for us to scale the number of cores which we did in Mininet.

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