Patch Panels in the Sky: A Case for Free-Space Optics in Data Centers

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ABSTRACT

We explore the vision of an *all-wireless inter-rack datacenter fabric*. Such a fabric, if realized, can offer operator the ability to dynamically reconfigure the network topology to adapt to future traffic demands while eliminating concerns related to cabling complexity. A key enabler for our vision is the use of free space optical (FSO) technology which, in contrast to traditional wireless/RF technologies, has lower interference footprint, can support longer range, and offers higher bandwidths. While FSO is an enabler, there are several significant practical challenges that need to be addressed before this vision turns into reality. We demonstrate the early promise of addressing these challenges and the potential benefits that this offers in comparison to state-of-the-art datacenter architectures.

Categories and Subject Descriptors

C.2.1 [**Computer Communication Networks**]: Network Architecture and Design

General Terms

Design, Experimentation, Management, Performance

Keywords

Data center, Free-Space Optics, Reconfigurable

1. INTRODUCTION

Data centers (DCs) are a critical piece of today's computing infrastructure that support key Internet applications. In this context, DC network designs must satisfy several potentially conflicting goals—performance (e.g., minimize oversubscribed links, low latency) [11, 19], equipment and management cost [11, 28], flexibility to adapt to changing traffic patterns [20, 30, 33, 36], incremental expandability to add new servers or racks [13, 31], and other practical concerns including cabling complexity, power, and cooling [16, 25, 27].

Given the highly variable and unpredictable nature of DC workloads [19], early DC designs offered extreme points in the space of cost-performance tradeoffs—either poor performance at low cost (e.g., a simple tree has many oversubscribed links) or expensive over-provisioned solutions with good worst-case performance (e.g., fat-trees for full bisection bandwidth [11]). Recent works suggest a middle ground that dynamically augments a simple fixed infrastructure with additional inter-rack wireless [20, 36] or optical links [33] to alleviate congested hotspots. While these do offer some performance benefits, we believe that they do not push the envelop far enough; e.g., they continue to incur high cabling complexity and may only handle specific traffic patterns.

In this work, we explore the vision of a *all-wireless inter-rack DC fabric*. This vision, if realized, would provide unprecedented degrees of flexibility for DCs. For example, it will allow operators to dynamically reconfigure the *entire* network topology to adapt to changing traffic demands. Similarly, it can act as an enabler for operators to deploy topologies that would otherwise remain "paper designs" due to the perceived cabling complexity.

Unfortunately, existing wireless/RF technologies are not suitable on two fronts. First, they incur a large interference footprint even with advanced phased-array antennas, especially when side lobes are considered [29]. Second, they suffer from a significant drop-off in data rates at longer distances [36], as federal regulations prevent use of higher power or wider bandwidth. In conjunction, these factors fundamentally limit the number and types of inter-rack links that can be created—an issue that exists even with newer designs to extend the range via ceiling reflectors [36].

Consequently, we look beyond traditional RF-based solutions and explore a somewhat non-standard wireless technology, namely *Free-Space Optics* (FSO). FSO uses visible or infra-red lasers to implement point-to-point data links, at very high data rates ($>$1 Gbps) and at longer ranges. (We elaborate on these in §2.) While the use of FSO in a general communications context is not new, there has been very lit-

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tle work to systematically explore the viability of FSO in the DC or highlight the benefits that FSO offers in this context.[1]

While FSO is an enabler, there are two significant challenges that need to be addressed. First, off-the-shelf FSO links cannot be cost-effectively reconfigured (i.e., realigned) at fast time-scales necessary in the DC context. Second, cost and physical constraints limit the number of FSO links that can be installed on the top of each rack. Thus, we need an effective topology design and management framework that can provide the desired performance and flexibility while operating under the physical and cost constraints.

In this paper, we discuss the viability of an FSO-based all-wireless inter-rack fabric and present early solutions to address the above challenges. To achieve fast reconfigurability, we leverage *switchable mirrors* that can be electronically controlled to act as mirrors or pass-through glasses. The use of switchable mirrors avoids the need for careful realignment (§3). We also discuss topology design and reconfiguration heuristics that seem to perform well in practice. We have built a proof-of-concept prototype using off-the-shelf FSO and switchable mirror solutions. Our early simulation results show that our approach provides superior performance compared to state-of-art DC networks of comparable cost (§4). We discuss extensions to our basic approach in §5, before concluding in §6. We discuss related work inline throughout the paper.

2. FSO: MOTIVATION AND VIABILITY

In this section, we provide background on free-space optics (FSO) and argue why this technology can serve as the "workhorse" for our goals.

2.1 Background on FSO

Free-space optical (FSO) communication [22] uses modulated visible or infrared (IR) laser beams in the free space to implement a communication link. Unlike traditional optical networks, the laser beam in FSO is not enclosed in a glass fiber, but transmitted through the air. There are two main benefits of FSO compared to traditional RF technologies (e.g., WiFi or 60 GHz) that make it a promising candidate for DCs:

(1) Low Interference and Bit-Error Rates. FSO uses very narrow laser beam widths, diverging with an angle of a few milliradians or less (1 milliradian = 0.0573 degree). This reduces the interference footprint to a negligible level. Thus, unlike traditional RF technologies, FSO communications from multiple senders do not interfere, unless the senders are aligned to the same receiver. Minimal interference and narrowness of the beams also results in very low bit-error rate.

(2) High Bandwidth over Long Ranges. Optical communications inherently provide significantly higher bandwidth than current RF technologies owing to the use of much higher frequency and absence of regulatory restrictions [22]. Coupled with much lower attenuation of power over distance, FSO links are able to offer higher data rates at long distances (several kms) even with modest transmit power (watts) [22]; e.g., commercially available FSO devices provide 2.5Gbps [1], and demonstration systems even report few Tbps [26].

[1]The only parallel work we are aware of is a recent patent document [15]. Unfortunately, this offers little in terms of viability analysis, design space arguments, or performance tradeoffs.

2.2 Feasibility of FSO in the Data center

The main stumbling block for traditional FSO communication comes from atmospheric elements (e.g., rain, fog, dust) and background radiation (e.g., sunlight). In the indoor and controlled environment of a DC, these challenges largely disappear. However, key challenges remain. First, commercially available FSO systems are bulky, expensive ($5-10K for a single link), and power hungry. Second, FSO beams require a clear line-of-sight, and thus, obstacle avoidance is a potential issue. (We defer the issue of beam alignment to the next section.)

Cost, Size and Power: Today's commercial FSO devices are relatively bulky $\approx$ 2 cubic feet of volume (e.g., [2]). This stems from many factors mandated by outdoor use-cases, viz., use of multiple laser beams to provide spatial diversity, elaborate alignment mechanisms needed for long distance use and recovery from building swaying, ruggedization needs etc. In contrast, a DC-centric FSO device can be conceptually built by repurposing commonly used optical small form-factor pluggable (SFP) transceivers [3]. The real difference between an optical SFP transceiver and an FSO device is that the former interfaces directly with an optical fiber instead of transmitting the laser signal through the air. Converting optical SFP to FSO entails the use of collimating lenses on the optical path and an alignment mechanism (e.g., precision positioners with a camera), though of a lesser level of complexity than that needed for alignment for outdoors and very long distances.

Several projects have demonstrated the viability of this approach without extra amplification [26, 32, 35], including one that uses commodity components [26] and one that targets Tbps speeds between buildings [12]. Given that 10Gbps SFP transceivers cost about US$250 [3], we estimate that an FSO device can be built for roughly $750.

With respect to size, SFPs themselves are small. After reviewing the basic design requirements of the mirror and alignment mechanisms, we believe that the entire assembly can be put together within about $\approx$ 3" x 8" 2D footprint that could provide a usable range of 100-200m [12, 26]. This range would normally cover the needs of most DCs. Finally, in terms of power, we note that with no additional amplification needed, the bulk of the power will be consumed in the SFP component, which is $\leq$ 1 watt.

Circumventing Physical Obstructions: If we have multiple FSO devices on the top of each rack, then the devices are likely to be obstacles for other links. We avoid this by leveraging ceiling mirrors [36]. Specifically, we avoid ob-

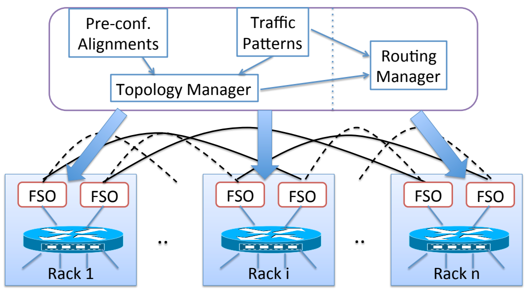


Figure 1: System overview: The Topology Manager decides the set of links to activate and the Routing Manager sets up routes for end-to-end flows. At any instant, only one candidate link per FSO is active (solid lines).

structions by directing FSO beams upwards and reflecting them from the ceiling mirrors (Figure 2). Conventional mirrors themselves can easily reflect visible and IR FSO beams with negligible loss (see §3.1) and thus, the cost of a ceiling mirror is negligible.

3. FSO-BASED INTER-RACK FABRIC

Our vision (see Figure 1) is a DC network where the ToR switches are interconnected using FSO devices. Note that we are not proposing a fully wireless DC [29]; our focus is on the inter-rack fabric. The FSO transceivers are placed on top of each rack and aligned to connect, after reflection from the ceiling mirror, to devices on other racks. We envision a centralized *Topology Manager* that dynamically reconfigures the inter-rack topology[2] and the *Routing Manager* acts in concert with the Topology Manager to setup routing table entries for each ToR switch to route flows between racks.

Ideally, we would like as many FSO transceivers on each rack and reconfigure the topology with zero delay. In practice, this is not possible. First, given that even a small FSO device is 3” x 8”, we can pack only few tens of FSO devices per rack of size 2’ x 4’. Second, existing steering mechanisms are not viable at the time/costs we envision: mechanical systems take a few seconds and non-mechanical solutions in the photonics community are still in their infancy [24]. While miniaturization and reconfiguration solutions for FSOs will likely improve over the next decade, our goal here is to work within these constraints and sketch a cost-effective architecture that is immediately within reach.

3.1 Reconfiguration via Switchable Mirrors

We leverage *switchable mirrors* (SMs) made from a special liquid crystal material that can be electrically controlled to rapidly switch between reflection (mirror) and pure transparent (glass) states [4]. We equip each FSO device with multiple SMs, and *pre-align* the SMs (using an offline steering assembly) to connect to an FSO on a different rack. As shown in Figure 2, a link is established by keeping one of

[2]And hence the title, our conceptual “patch panel” to reconfigure the topology is “in the air”!

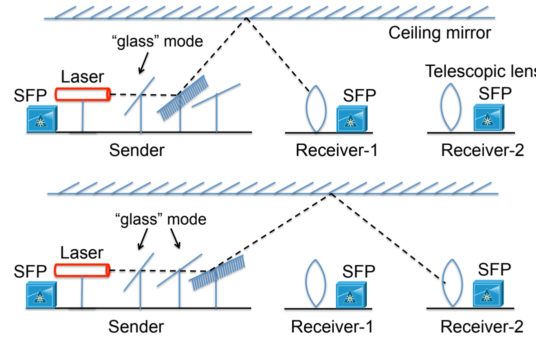


Figure 2: In the top half, the second SM is in mirror state, and directs the FSO beam to receiver1. In the bottom half, only the third SM is in mirror state, which directs the beam to receiver2.

the SMs in mirror state and the other SMs in that FSO in transparent state. (An analogous configuration exists at the other end to create a duplex link, but not shown.) In essence, the pre-alignments of the SMs yield a set of *candidate* links. At any instant, only one of the candidate links is *active* per FSO based on the SMs’ state. (See Figure 1.) When manufactured at scale, each small-size SM will cost < $5 [23].

Proof-of-concept: We built a proof-of-concept prototype to evaluate the viability of switchable mirrors. As a pragmatic choice, we use off-the-shelf components: (1) LightPointe FlightStrata G Optical Gigabit Links [2]; (2) A 12” x 15” switchable mirror (SM) from Kentoptronics [4] tuned for IR spectrum; and (3) normal mirrors.[3] We found that the switching latency of the SM was around 250 ms. Because the switching latency is proportional to the SM’s surface area [5], we conservatively estimate a 20 ms latency for the (1” x 1”) SM we propose to use. We also confirmed that the FSO beam is reflected from conventional mirrors with negligible loss and achieves full achievable bitrate.

Degree of Reconfigurability. In practice, size constraints will likely limit the number of SMs per FSO device. In our current architecture, we conservatively assume that it is feasible to add 5-10 SMs on an FSO device, with the overall device still ≈ 3” x 8” in size. Our design using a finite number of SMs provides a sufficient degree of reconfigurability (i.e., activating some subset of candidate links by switching states of SMs) at fast timescales.[4] Reconfiguration using SMs effectively removes the need to *realign* the FSO devices. Furthermore, since the pre-configuration is done relatively infrequently, it need not be achieved at a fast timescale.

Our remaining tasks are: (1) Choose an appropriate *pre-configured* topology (i.e., candidate links defined by the SMs’ pre-alignments); and (2) Design dynamic reconfiguration mechanisms (i.e., activating select links) to adapt to traffic patterns. We discuss these next.

[3]The prototype is larger than the 3” x 8” form factor we envision as the equipment is designed for outdoor use.

[4]Even though mechanically steering the SMs/FSOs provides full reconfigurability, this takes few seconds or minutes.

3.2 Pre-configured Topology

Our goal in this paper is not to design an optimal pre-configuration topology. Rather, we want to demonstrate the potential benefits of an FSO-based inter-rack design. To this end, we discuss two promising starting points.

Regular Random Graphs: Recent work shows that random regular graphs provide bandwidth and latency comparable to structured topologies [31]. Furthermore, a random graph is naturally amenable to incremental expandability. If each FSO is equipped with k SMs, then we create a k-regular random graph over the FSOs by aligning the SMs appropriately. In fact, FSOs act as an enabler to leverage the benefits of such structures by eliminating potential concerns about the wiring complexity and mis-wiring (see [31], Section 6).

Hypercube + Random Links: If the node degree is low relative to the number of racks, a random graph may not have good connectivity. This might become relevant in the regimes we are considering—degree is a few tens, and number of racks/nodes may be a few hundred. Thus, we consider an alternative topology where we use some SMs to construct a "baseline" topology that guarantees connectivity properties, and align the remaining SMs randomly.

We believe that a hypercube is a suitable baseline topology for three reasons: (1) it uses a small number of links and leaves many candidate random links; (2) it has a small diameter ($\log n$ for n racks); and (3) it has high bisection bandwidth ($n/2$ over n racks). Furthermore, the performance of a hypercube can be improved by adding *diagonal* edges which connect each node to its "complement"; these "short-cuts" halve the diameter (proof omitted). We also conjecture based on simulations that the diagonals also improve (roughly double) the bisection bandwidth.

3.3 Dynamic Reconfiguration

We have two sub-tasks here. First, given a pre-configured topology, we need to choose a suitable set of active links out of the candidate links depending on current traffic patterns. Second, unlike prior hybrid architectures [17, 33, 36]), our network does not contain a fixed wired backbone. Thus, one potential concern is that reconfigurations (by changing the states of SMs) may result in transient connectivity problems. We sketch solutions to address each challenge.

Reconfiguration Strategy: Designing an optimal strategy is challenging because DC workloads are diverse and hard to predict [19]. Our goal is not to seek optimal solutions, but a feasible yet performant architecture. To this end, we use a heuristic based on prior work [14, 17]:

- Short flows (e.g., $\leq$ 1MB [14, 17]) are routed along the shortest path formed by currently active links.
- For large flows (i.e., $>$ 1MB), we evaluate if activating some link(s) can provide higher throughput than routing it over the current network. In our current design, we only activate links that yield a shorter and/or less-congested paths to the destination.

We can extend this along several dimensions as discussed in §5. As such, the quantitative benefits we show in §4 can be viewed as an immediately achievable lower bound of the benefits our vision can offer.

Lossless Reconfiguration. Given the finite latency involved in changing SM states, we need to ensure that we don't drop packets or disrupt the flow of latency-sensitive packets during this transition. At a high-level, we achieve this by ensuring that there is always a "valid" routing table even during reconfigurations; i.e., each entry corresponds to an active link. To see the intuition behind our approach, we start with a simple reconfiguration to activate a single edge (x, y), between FSO devices x and y, and deactivating the currently active links (x, w) and (y, z). The key here is in the ordering of the steps—we remove routes before deactivating links and add routes only after activation is complete as shown below:

1. Avoid this reconfiguration, if deleting active links of the type (x, w) or (y, z) (to free the FSOs x and y) will disconnect the network.[5]
2. Update the routing table to reflect removal of links (x, w) and (y, z).
3. Switch the states of appropriate SMs to: (i) deactivate links (x, w) and (y, z), and (ii) activate the link (x, y). Note that this step can take $\approx$ 20 ms.
4. *After* completion of the above step, update the routing table to reflect addition of link (x, y).

We may need to handle multiple potential reconfigurations that occur almost simultaneously in response to traffic changes. Multiple reconfiguration can be handled in one of three ways: (i) one at a time, (ii) in batches (i.e., queue and combine them into a single reconfiguration); and (iii) execute each reconfiguration individually but *concurrently*. The first two options can be inefficient as large flows wait until the desired link(s) become available. We believe that the third option can be achieved by a careful implementation of step #1 above.

4. PERFORMANCE BENEFITS

In this section, we use a custom simulator to compare the performance of our FSO-based architecture(s) against state-of-art DC designs. As a representative point, we consider a DC with 24,576 machines organized into 512 racks of 48 machines. Our results are qualitatively similar for other configurations.

Candidate Architectures and Costs. The specific architectures we consider are:[6]

[5] To ensure that a reconfiguration request is *never* rejected, we can use some of the FSOs per rack to implement a static connected graph (e.g., ring) and never change these links.

[6] We don't consider the all-wireless architecture of [29] because it has worse cost-performance tradeoffs relative to the below architectures; e.g., for 24k machines, it costs $\approx 50M$ (based on \$1k for a 60GHz radio) but only achieves 300-400 Mbps per-server and has an average/max. hop-count of about 10/100 [29].

Architecture	Cost ($)	Effective per-server throughput
FSO-based (16,5)	18.1M	1.7 Gbps
3D Beamforming	17.1M	1.1 Gbps
Fattree/Jellyfish 1Gbps	13M	1 Gbps
Fattree/Jellyfish 2 Gbps	26M	2 Gbps
FSO (48,10)	37.8M	8.5 Gbps
Fattree/Jellyfish 10Gbps	57M	10 Gbps

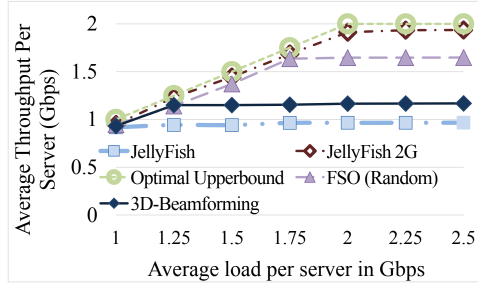
Table 1: Cost-performance tradeoffs for 512 racks with 48 machines/rack: The FSO designs are specified by (#FSOs, #SMs/FSO).

- **Fat-tree [11]:** We consider 1Gbps and 2Gbps bisection-bandwidth FatTree networks. A 2Gbps network is essentially two 1Gbps networks put together.
- **Jellyfish [31]:** We construct wired random graphs [31] and similar to FatTree, we consider both 1 and 2 Gbps architectures.
- **3D-Beamforming [36]:** We use a wired 1Gbps bisection-bandwidth network augmented with eight 60GHz wireless radios per rack [36]. We conservatively assume 0.01s antenna rotational delay (lower bound from [36]), no interference, and a 1-10 Gbps bandwidth for wireless links based on inter-rack distances [36].
- **FSO-based designs:** We use two pre-configured topologies (§3.2): (1) `Random` and (2) `Hypercube+`. We use a 64-port 10Gb ToR switch [6]; 48 ports connect to machines and 16 ports to FSO devices. Each FSO link is 10 Gbps, since we use 10Gbps optical SFPs as our cost basis. We assume each FSO device has 5 SMs, with a switching latency of 20 ms.

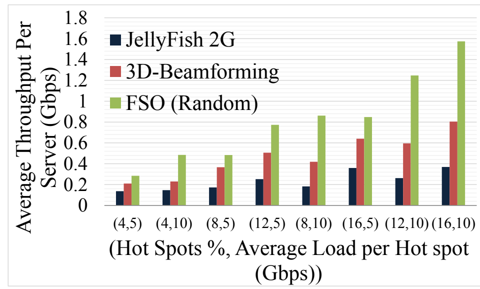
Ideally, we want to compare architectures by normalizing their cost. Unfortunately, some architectures (e.g., Fat-tree, `Hypercube+`) do not admit a continuous spectrum of cost-performance tradeoffs. Further, some of these cost estimates are moving targets. As such, we pick configurations where the costs are roughly comparable based on estimates we obtain as discussed below.

We assume that a 64-port 10Gb ToR switch for the FSO designs costs $27K: $11K for the bare switch [6], and $16K for 64 10Gbps optical SFP+ transceivers at $250 each [3]. We assume that a 48-port 1Gb switch costs $5000 [7], and each 60GHz radio costs $1000. From §2, each FSO device costs an additional $\approx$ $500 with $5 for a small-size SM, when manufactured at scale [23]. We assume ceiling mirrors (for FSO and 3D-beamforming) have negligible cost and we conservatively ignore cabling costs for the wired architectures. Given the above assumptions, Table 1 summarizes the costs. Here, Fat-tree/Jellyfish 1Gbps use 2600 48-port 1Gb switches. We see that FSO-based designs roughly fall between the 1 Gbps and 2 Gbps wired architectures. As additional points of reference, the table also shows 10 Gbps architectures for FSO and Fat-tree (discussed later).

Simulation Setup. For scalability, we consider a flow-level simulation using a fluid model, and do not model packet-level or TCP effects. We use synthetic traffic models based on prior measurement studies as follows [19, 36]. We consider a *baseline* workload where, for each pair of machines, flows arrive independently based on a Poisson distribution with a *arrival-rate* λ/s, with the flow size distribution measurements from production DCs [19]. We refer to this as the `Uniform` workload. Prior studies have observed hotspots between pairs of racks [19]; thus we consider the `Hotspot` model where in addition to the `Uniform` baseline, we use a higher arrival-rate λ_2 and a fixed flow-size of 128MB for a subset of machines chosen as follows [36]. We randomly pick $x\%$ of machines, and for each one of them, we pick $x/2\%$ of machines as their destinations with a slight bias [36]; we vary λ_2 and x in our simulations.



(a) Uniform

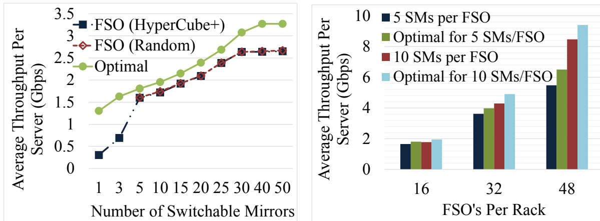


(b) Hotspot

Figure 3: Average per-server throughput for the `Uniform` and `HotSpot` workloads. The x-axis shows the average load per server which is a product of arrival-rate (per pair), number of servers (512), and average flow size. The result for Hypercube+ is identical to Random and the result for Fat-tree is identical to Jellyfish and are not shown.

Throughput and Latency. Figure 3(a), shows the average per-server throughput for the `Uniform` workload. We observed that Jellyfish and Fat-Tree architectures are nearly identical and the two FSO-based architectures (Random and Hypercube+) also have the same performance. For ease of presentation, we omit plots for Fat-Tree and Hypercube+.

We see that FSO-based architectures provides 1.7Gbps of average throughput per server, which is significantly higher than 1Gbps Jellyfish/Fattree and 3D-Beamforming, but slightly lower than the 2Gbps Jellyfish/Fattree. As a point of reference, we compute an upper bound on the *optimal* throughput achievable with FSOs. Given a configuration of # FSOs per rack and # SMs per FSO, we compute this bound by estimating the minimum possible average shortest-path length; we omit the details due to space limitations. We see that our design performs quite close to the upper-bound of $\approx$ 2Gbps.



(a) Vary #SMs (b) Vary #FSOs

Figure 4: Sensitivity analysis, varying number of FSOs and number of SMs using the baseline `Uniform` workload

For the `HotSpots` workload in Figure 3(b), as in [36] we use a low baseline load of 0.1Gbps average load per server.[7] We consider different configurations for the number of hotspots and intensity (i.e., $x\%$, average load per hotspot) as shown. First, we see that all flexible architectures (FSO-based and 3D-Beamforming) outperform the static Jellyfish (and Fat-Tree) 2Gbps designs. Second, the FSO-based design outperforms 3D-beamforming by large margin (30 to 100%).

We also measured the latency in terms of inter-rack hops per-packet. The average, 95%ile, and max latency for FSO-based proposals were 2.5, 6, and 12 hops respectively (not shown). In comparison, the corresponding numbers for Fat-tree and Jellyfish are 3.9,4,4 and 2.5, 3, 5 hops respectively. We see that in the common case, FSOs provide low latency, but in some very rare cases we incur longer paths.

Sensitivity Analysis. The previous results consider a fixed number of FSOs per rack and SMs per FSO device. In Figure 4, we vary (a) the number of SMs keeping the number of FSOs at 16/rack, and (b) the number of FSOs per rack for 5 and 10 SMs/FSO. (We do not show `Random` for less than 5 SMs, since it does not form a connected graph.) First, we see that the effective per-server bandwidth increases with the increase in SMs, but saturates at around 30 SMs per rack (when we almost get a complete candidate graph). Second, the configuration of 48 FSOs with 10 SMs provides almost 8.5Gbps.

Given our current size estimates, it is actually feasible to place 48 FSOs on each rack; the total cost of this architecture is ≈ \$38M. We estimate this assuming a 96-port 10Gb switch (hypothetically) costs \$49k (= \$25k for the switch + cost for 96 SFP+ modules at \$250 each). In comparison, a 10Gbps Fat-tree architecture would (conservatively) cost around \$57M assuming each 48-port 10Gb switch costs \$22k (= \$10k [8] + cost for 48 SFP+ modules).

5. DISCUSSION

Rethinking Metrics of Goodness. Traditional metrics such as bisection bandwidth and diameter largely reflect a *static* perspective of the topology. For the types of flexible networks we envision, we need to rethink these metrics; e.g., we need a notion of *dynamic* bisection bandwidth based on the best achievable bandwidth by some *realizable* topology for a given network partition.

Optimal Topologies. Given new dynamic performance indices, we need to reason about the pre-configured alignment of SMs that optimizes these metrics. While the random and extended hypercube designs work well, we do not know if these are provably (near-)optimal. Furthermore, choosing an optimal run-time topology is effectively an online optimization problem—given a pre-configured topology, current configuration and traffic patterns, what is the best way to reconfigure the network? What makes this challenging is that even the offline version of this problem is intractable.

FSOs for Modularized Data centers. While our current work focuses on the inter-rack fabric, FSOs might also be useful for containerized architectures [17]. This context introduces new challenges and opportunities. Specifically, a ceiling mirror is not feasible in outdoor scenarios and we need other mechanisms (e.g., vertically steerable FSOs?) for line-of-sight. At the same time, the coarser aggregation may permit higher switching latencies and thus be amenable to slower (mechanical) steering mechanisms that can provide full reconfigurability.

Multipath and Traffic Engineering. We could further improve the performance using multi-path TCP [34] or better traffic engineering [18]. We posit that multi-path TCP has natural synergies with reconfigurability as it can alleviate transient congestion and connectivity issues.

Other Benefits. In addition to the quantitative benefits we explored, FSO-based flexible architectures also offer other qualitative advantages. First, by acting as an enabler for new topologies, it naturally inherits the properties they provide; e.g., random graphs offer incremental expandability [31]. Second, selectively disabling links may also decrease energy costs [21]. Furthermore, by eliminating the wired infrastructure, FSOs can potentially reduce cooling costs by avoiding problems due to airflow obstruction [10].

6. CONCLUSIONS

We explored an FSO-based inter-rack fabric for data centers, a solution whose benefits have been suggested [9, 15], but has received little attention in depth. We showed that FSOs can be viable with the extensions we propose (e.g., switchable mirrors and pre-configured topologies). Our evaluations show that FSO-based designs offer good cost vs. performance tradeoffs (Table 1) w.r.t. state-of-art solutions; e.g., close to 9 Gbps bisection bandwidth at much less cost compared to a Fat-tree, and 90% of the performance for 2 Gbps fat-tree at 70% of the cost. We note that these benefits only represent an early starting point—miniaturization and commoditization will further improve the cost-performance tradeoffs and flexibility that FSO-based designs can offer.

[7] We also tried other baseline loads. FSO outperforms other solutions under all scenarios, but the relative gain decreases at higher load as there is less scope for improvement.

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