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GUIDE

Key Considerations for Architecting a High-Performance Fabric

INTRODUCTION FROM ADDISON SNELL,
INTERSECT360 RESEARCH

Foreward

> *In this paper, we look at the top considerations and trends when architecting today's High Performance Computing (HPC) clusters based on industry trends and ongoing interactions with customers, partners, and subject-matter experts. The forward is provided by Addison Snell from Intersect360 Research, a leading market intelligence, research, and consulting advisory practice focused on suppliers, users, and policy makers across the High Performance Computing industry. It offers context for the market dynamics at play as new workloads in data intensive structures challenge performance expectations for HPC networks.*

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Market Dynamics
By Addison Snell, Intersect360 Research

A CHANGING MARKET

HPC is a long-term stable market due to the inexhaustible nature of scientific advancement. As long as there are questions left unanswered in the universe, research will strive to solve them, applying computational modeling and simulation along the way. Furthermore, scientific understanding leads to practical advancements in R&D, engineering, and product development, fueling innovations in industries like manufacturing, pharmaceuticals, and energy. More than half of HPC usage, by spending, is commercial. [Intersect360 Research, 2022]

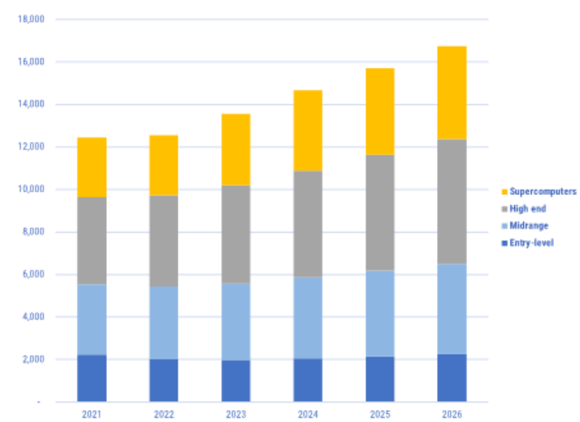
Beyond this foundational underlying need, HPC continues to expand into new use cases. In the mid-2010s, the Big Data revolution brought attention to analytics as a pathway to competitive advantage, activating hidden knowledge in enterprise data. Today, artificial intelligence (AI) is taking that a step further, with deep neural networks finding patterns in pre-existing data that can be applied to new conditions.

AI is fueling incremental investment in HPC technologies. Among experienced HPC users, more than two-thirds (68%) have already implemented machine learning as part of their HPC environments, with an additional 11% planning to do so within the next year. And among those that have already done so, more than 50% have seen an increase in their HPC budgets directly related to machine learning. [Intersect360 Research, 2022]

Beyond the HPC-using crowd, Intersect360 Research is tracking a small but growing market for on-premises infrastructure for AI projects that are in no way related to HPC budgets or environments.

Counting this "pure AI" spending, the combined market for on-premises systems for HPC and AI training will grow to $18.7 billion in 2026. This growth will be particularly concentrated toward larger systems, which have a greater need for scalable, high-performance system interconnects.

Figure 1 - Worldwide On-Premises HPC and AI System Spending ($M) by System Class, 2020-21 Actuals, 2022-26 Forecast, Intersect 360 Research, 2022



The growth in HPC system demand, combined with the trend toward larger systems, shines a light on system interconnects as increasingly important to discovery and innovation.

PERFORMANCE – MORE THAN JUST BANDWIDTH

The essence of HPC is to run a single application over many processing elements, thereby distributing the work to run the application to completion faster. Within this context, the system interconnect is one of the key enablers to achieving performance at scale. Tightly coupled HPC applications often encounter dependencies in data movement or calculations, causing one node to wait for information from another.

Two important concepts—bandwidth and latency—define system networking performance.

For HPC, the need for higher-performing networking is perpetual. HPC systems represent a significant investment. In a recent Intersect360 Research survey, the importance and urgency of interconnect performance shows up among HPC users.

> *In a recent Intersect360 survey, 66% of respondents rated both "system network bandwidth" and "system network latency" as either important or very important.*

Regardless of architecture, many HPC networks struggle to manage a phenomenon that is familiar to any commuter: traffic. Even on an eight-lane freeway, a car might not travel at its top speed if other cars are in the way, thereby increasing the travel time. Conflicts over bandwidth lead to increases in latency. One node in a cluster might do fine on its own but suffer from a so-called "noisy neighbor" that commands the available nearby resources.

While this is theoretically true of any enterprise network, it is important in HPC, because nodes in a parallel computation have to move in lockstep, and advancement is gated by the completion of the slowest communication. In a group of many nodes, one significant contention can have ripple effects across the entire network. Therefore, in gauging performance, the average or typical latency is often not as important as the "tail latency," i.e., how long the slowest thing takes.

Consider, in a party of five people, if four can each cross a bridge in one minute, but one takes six minutes, how long would it take the entire party to cross? The average time of two minutes doesn't matter at all. The group is gated by the slowest time.

If tail latency is a defining characteristic of latency for HPC, then the similarly important aspect of bandwidth is "bisection bandwidth," which measures the aggregate cross-system bandwidth of a network, regardless of which way it is bisected. Back to our car traffic example, consider a city grid in which the north-south roads are multilane thoroughfares, devoid of impediments, but the east-west avenues are meager, single-lane, potholed slogs.

Total travel time will be determined more by how much east-west travel there is than north-south, and no amount of going north solves the problem of needing to go west. In a computer network, bisection bandwidth measures the total aggregate system bandwidth of the more limited direction, which can be a more accurate indicator of system performance than the total aggregate bandwidth.

A NEW STANDARD FOR HIGH-PERFORMANCE NETWORKING

About half the HPC market is served by Ethernet clusters. This industry standard tends toward the lower-performance side of HPC in terms of bandwidth and latency, and it often serves application workloads that are less scalable or less tightly coupled. The high-performance end of the HPC market is currently dominated by InfiniBand, which gained popularity as a high-bandwidth, low-latency standard in the early 2000s. The HPC market has remained relatively stable, balancing these two alternatives through generations of computing.

There are reasons to believe this dynamic has begun to change. InfiniBand was once an independent standard with multiple vendors, but Mellanox soon became the de facto sole producer of InfiniBand networking. In 2020, Nvidia completed its acquisition of Mellanox, and while this doesn't necessarily change the technology or its roadmap, it calls into question how well InfiniBand might continue to mesh with processing elements from Nvidia's competitors, Intel and AMD.

Meanwhile, some system vendors have begun to ship their own proprietary interconnects for supercomputers at the apex of the market; these include Slingshot (proprietary to HPE), BXI (Atos), and Tofu (Fujitsu). At present, none of these threatens to escape their single-vendor status or super-scalable niche.

The opportunity exists to establish a new standard for high-performance networking. Such a solution would need to address traditional challenges in scaling both bandwidth and latency on trafficked networks, while remaining available to work optimally with systems and processing elements from multiple vendors.

Architecting a High-Performance Fabric

The Network Is no Longer an Afterthought

Network architects have traditionally had many options to consider on both the compute and storage sides when building new clusters for high-performance computing (HPC), artificial intelligence (AI), machine learning, deep learning, and other performance-intensive computing (PIC) workloads. They could consider technology options for:

- Overall scale
- Compute type (CPU, GPU, FPGA)
- Compute architecture and core density
- Parallel file systems
- Burst buffers
- Network oversubscription
- Network redundancy

When it came to high-performance interconnects, however, InfiniBand was the default choice. Some clusters deployed a second network for storage access — usually based on Ethernet — to avoid the latency impact of bulk data flows on the InfiniBand network.

7 Key Considerations for Optimizing Network Design

Recently, new network architectures were introduced to address many of the inherent limitations common to centralized InfiniBand and Ethernet switched networks. These modern architectures allow true optimization of the overall cluster design, resource utilization, and decisioning insight.

With new networking options available, network architects must now consider a number of factors related to networking in addition to traditional considerations. For example, they must think about how to:

- Maximize compute and storage usage through bisection efficiency
- Make optimal use of available power
- Ensure the network can scale linearly without artificial break points
- Design networks for heterogenous workloads
- Deliver network resiliency
- Test the network to accurately measure performance
- Familiarize staff with deployment and management of the chosen interconnecttechnology

To design and build a modern fabric that meets the current and future needs of both compute- and data-intensive workloads, it's important for network architects to understand how and why each of these considerations influences interconnect performance.

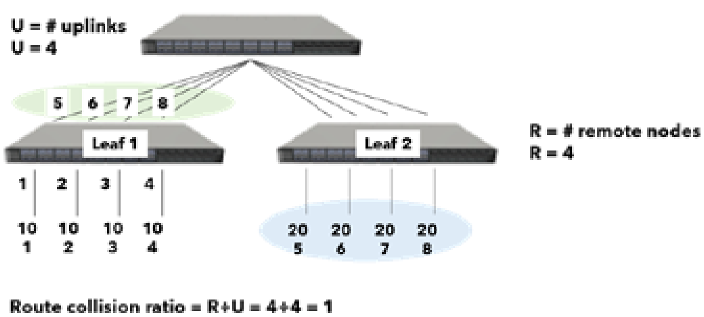
1. Maximize Compute and Storage Usage Through Bisection Efficiency

Network bisection is a measure of the maximum theoretical total bandwidth a network can support from one side to the other. Most network architects are aware that bisection is a very important metric when judging the potential performance of an interconnect design. But the key word in the definition of bisection is "theoretical."

Achieving full bisection of bandwidth requires perfect routing information, in which the entire real-time state of the network is precisely known.

> *With perfect knowledge of how busy each link is and the exact traffic pattern expected from all applications, traffic can be perfectly routed to make use of all bandwidth (Figure 2). This is impossible in practice.*

Figure 2 - Theoretical "Perfectly Subscribed" Switching Architecture



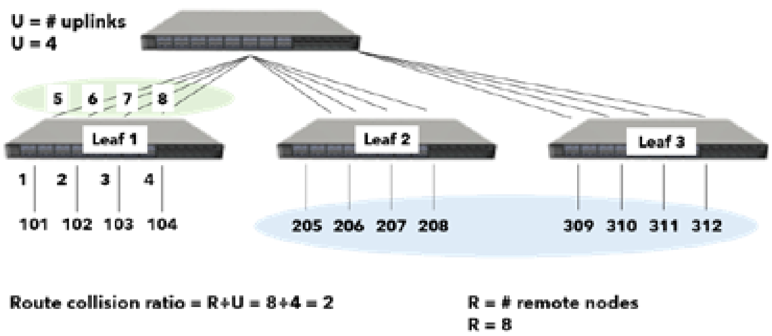
Leaf 1 Route Table

Port	LID(s)
1	101
2	102
3	103
4	104
5	205
6	206
7	207
8	208

ROUTE COLLISIONS ARE INEVITABLE IN TRADITIONAL SWITCH-BASED ARCHITECTURES

In real-world networks, information about network state and global traffic patterns is limited, so networks make routing decisions based on partial information. This leads to imperfect decisions, and inevitably means some network links are heavily overloaded and congested while others remain idle (Figure 3).

Figure 3 - Route Collisions in Traditional Switch-Based Architecture

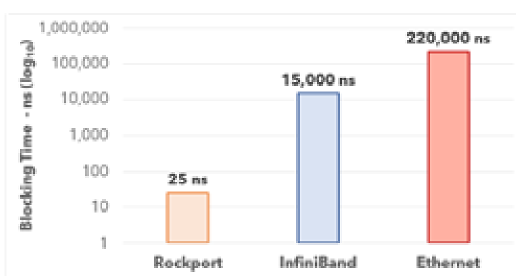


Leaf 1 Route Table

Port	LID(s)
1	101
2	102
3	103
4	104
5	205
6	206,309, 310
7	207, 311
8	208, 312

Cerio customers who also use traditional network architectures report that 90% of traffic travels over 20% of the available links. These overloaded links lead to extremely high tail latency, up to 15 microseconds per switch, which has a very significant impact on workload completion times (Figure 4).

Figure 4 - Network Latency Due to Overloaded Links



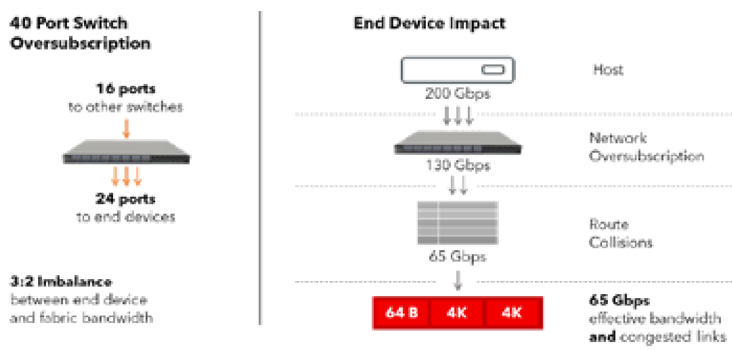
This latency also limits job scale because larger jobs require more inter-process communication (IPC), which makes them more sensitive to network congestion.

ELIMINATING OVERSUBSCRIPTION WON'T ELIMINATE THE PROBLEM

Unfortunately, the route collisions and inefficient use of links in traditional networks mean links continue to be overloaded, even when the network is designed with no oversubscription. Because the problem can't be solved by simply increasing link bandwidths, it persists even when the latest generations of network switches are used. In fact, for bandwidth-heavy workloads, network architects would have to greatly undersubscribe the network to compensate for traffic flow issues and achieve expected performance levels.

The problem is compounded by oversubscription, which traditional network architectures use to decrease cost and increase scale. In the case of 3:2 oversubscription, the amount of theoretical network bandwidth available is reduced by roughly one-third (Figure 5). In a 200 Gbps network, that means 130 Gbps of bandwidth is actually available. However, route collisions cut that number in half, leaving only 65 Gbps of effective bandwidth.

Figure 5 - Typical Oversubscription Reduces Available Bandwidth by Almost Two-Thirds



As oversubscription increases, bisection efficiency decreases (Table 1).

NO OVERSUBSCRIPTION			2:1 OVERSUBSCRIPTION	
Output Port at 200 Gbps	**Number of Destination Nodes Sharing Output Port**	**Bandwidth per Destination Node**	**Number of Destination Nodes Sharing Output Port**	**Bandwidth per Destination Node (2:1)**
1	2	100 Gbps	4	50 Gbps
2	3	66 Gbps	6	33 Gbps
3	4	50 Gbps	8	25 Gbps

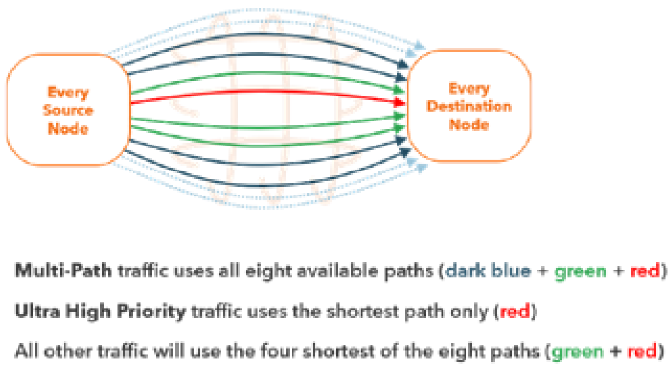
Table 1 - Increasing Oversubscription Decreases Bisection Efficiency

VERY HIGH PATH DIVERSITY MAXIMIZES BISECTION EFFICIENCY

The combination of theoretical bisection bandwidth and how efficiently the network architecture can use it drives true performance.

Modern network architectures use multiple concurrent parallel paths through the network with per-flow or per-packet adaptive routing to achieve maximum bisection efficiency (Figure 6). In contrast, some traditional network architectures use static per-destination routing, which results in high levels of wasted bisection bandwidth.

Figure 6 - Very High Path Diversity in Modern Networking Architectures



Even if traditional networks sense congestion in the network, they shift all traffic from one source and destination pair to another single path, replicating the initial problem. In fact, a recent IEEE paper concluded: "In congestion scenarios adaptive routing spreads congestion to a larger part of the network than what is the case with deterministic routing."[1]

In practice, network operators Cerio has spoken to report turning off adaptive routing because it causes rather than solves performance issues. The same is true for quality of service (QoS), which network operators find too difficult to configure and manage, and which requires a system reboot to change service levels.

A more efficient network means compute and storage resources are also used more efficiently because they aren't left idle due to network congestion. These combined efficiencies enable clusters to run workloads faster, run more workloads over time, and allows jobs to be run at much higher scale. For some workloads, end users can expect up to 30% faster workload completion times, making network efficiency a key consideration in a cluster architecture.

[1] Rocher-Gonzalez, Gran, Reinemo, et al: Adaptive Routing in InfiniBand Hardware, CCGrid 2022. fcrlab.unime.it/ccgrid22

2. Optimize Available Power

For many network architects designing new clusters, energy efficiency is now a top priority. They're motivated by physical power or cooling limitations, and by organizations' increasing focus on creating more sustainable systems.

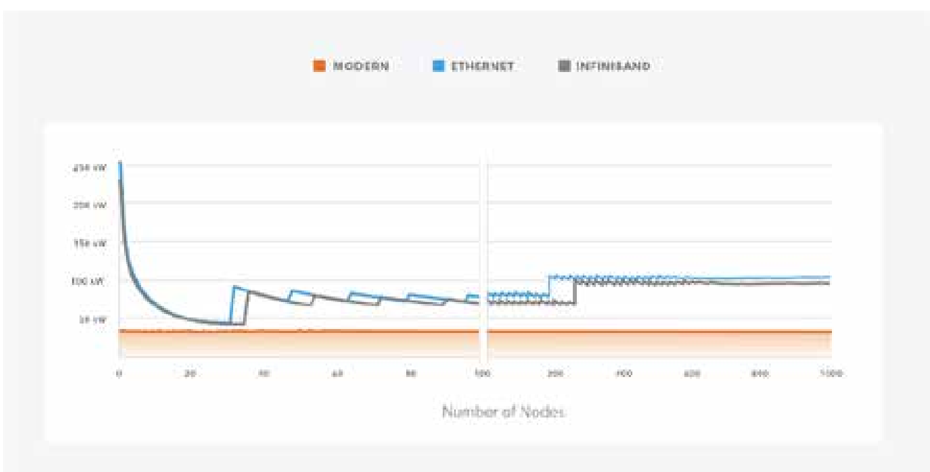
Traditional network architectures are very power-inefficient and require high power-per-node to achieve very high scales. Many traditional switches consume so much power that liquid-cooling becomes mandatory.

As traditional switch architectures have evolved to higher bandwidths, so has their requirement for higher power levels. High-bandwidth switches, transceivers, and host interface cards consume much more power than their predecessors, making the network a significant contributor to overall power consumption in the cluster.

Modern network architectures are designed with power efficiency in mind. By leveraging very efficient transceiver technologies, overall power consumption can be reduced by up to 70% compared to traditional architectures.

In fixed-size clusters, power-efficient transceiver technologies can drive tremendous power and cooling sav-ings. In other clusters, power efficiencies mean more compute and storage resources can run within the same power and cooling envelope for more efficient use of available power.

Figure 7 - Spikes in Power Use as Networks Scale



3. Ensure Network Scales Without Artificial Break Points

HPC clusters rarely remain static. As annual budgets are assigned and end-of-year funding is released, there are at least a couple of opportunities each year to grow existing clusters.

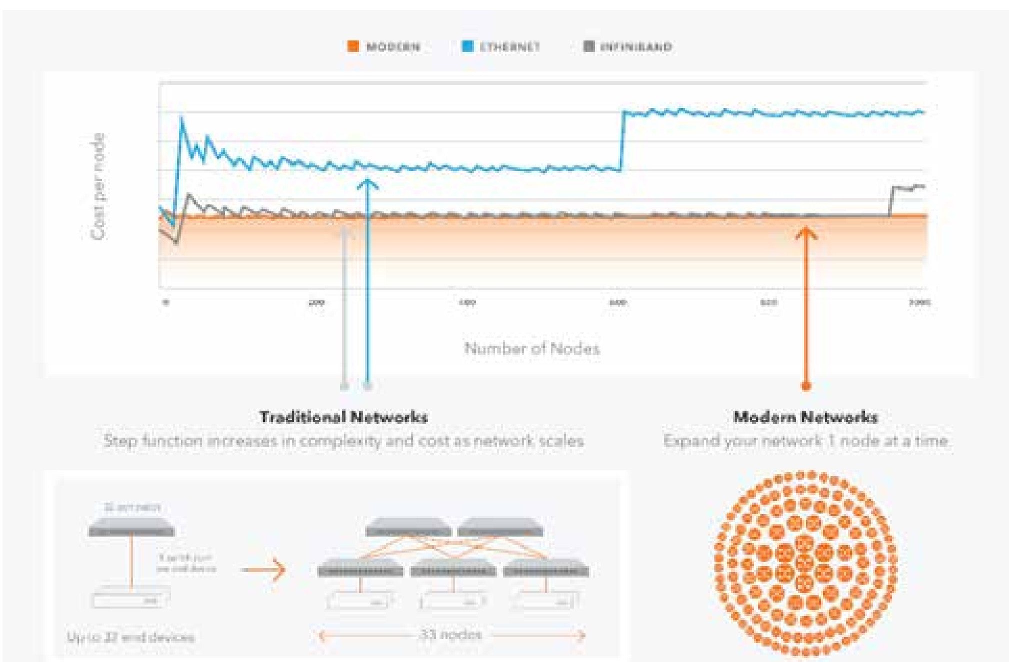
Traditional network architectures have inherent scaling limitations that make it very challenging to seamlessly scale clusters. The initial choice of network switch radix (port count) and oversubscription ratio create hard limits that require expensive, complex, and lengthy rewiring efforts that lead to significant downtime and opportunities for errors.

Consider a network based on 32-port switches. If there are close to 32 nodes, there is a good fit. However, if the network grows to 33 nodes and you want to retain non-blocking operation, you now need to purchase four additional switches and rewire the existing nodes to create a spine-leaf topology. There is also inherent waste if the cluster can't make use of all of the switch ports. This can be true for small-scale clusters with eight to 10 nodes as well as large-scale clusters where the rack and data center layout mean unused ports are common.

In addition, scaling the network and adding switches also decreases bisection efficiency because there are more route collisions and latency spikes.

Modern network architectures are designed to easily scale in place with no artificial scaling limitations. Network architects can scale networks as budget and end-user requirements demand, in scalable units or in smaller increments.

Figure 8 - Cost Increase for Scaling Traditional Versus Modern High-Performance Network



4. Design for Heterogenous Workloads

The vast majority of HPC clusters simultaneously run more than one workload. However, even communication within a single job can introduce congestion and impact other nodes in that job. These multi-workload environments encompass a wide range of jobs, each with sensitivities to latency performance, bandwidth performance, or both. As AI, machine learning, and deep learning jobs increasingly run alongside traditional HPC workloads, the heterogenous nature of multi-workload environments increases.

Traditional high-performance networks can struggle to maintain adequate performance when running heterogenous workloads. They can be tuned for latency performance or bandwidth performance, but not both. As a result, network architects are forced to compromise and job performance is significantly impacted by noisy neighbor jobs that share the same network.

The issues with this compromise are confirmed in an IEEE paper on networking performance. The paper found that "the tested IB switch can either provide low latency to a latency-sensitive flow or high bandwidth for bandwidth-intensive flow(s), but not both simultaneously...the switch fails to protect the latency-sensitive flows from bandwidth-intensive ones, and latency is proportional to the number of active bandwidth-hungry flows." [2]

From a cost and simplicity standpoint, network architects often want to deploy a single network for IPC and storage access. However, storage traffic then becomes yet another noisy neighbor, degrading workload performance across the entire cluster.

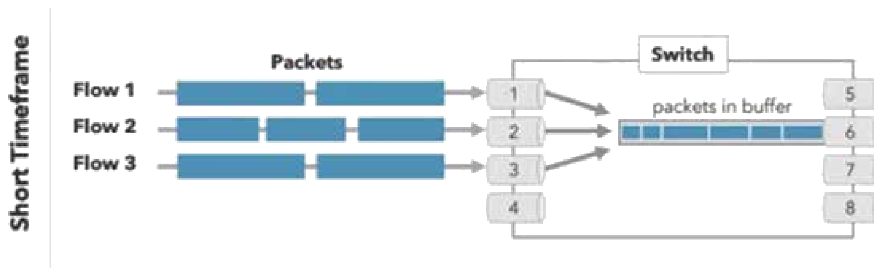
[2] **M. R. Siavash Katebzadeh; Paolo Costa; Boris Grot: Evaluation of an InfiniBand Switch: Choose Latency or Bandwidth, but Not Both**, In Proceedings of 2020 IEEE International Symposium on Performance Analysis of Systems and Software.

HETEROGENEOUS WORKLOADS INCREASE NOISY NEIGHBOR ISSUES

The more heterogeneous a traditional high-performance network is, the more noisy neighbors will be present, and the more often traffic will converge on the same switch output port. At small time scales, the switch will buffer the excess traffic, which leads to latency spikes, driving higher tail latency and extending workload completion times (Figure 9).

The heavier the traffic flows, the more long lived these noisy neighbors are, and the worse the problem is. It doesn't matter whether noisy neighbors are accessing storage or feeding GPUs data for AI or machine learning applications, the problem will persist.

Figure 9 - Colliding Traffic Leading to Latency Spikes



A SINGLE NETWORK FOR MODERN WORKLOADS

To deal with the noisy neighbor issue, many organizations are deploying a completely separate network — usually Ethernet-based — for storage access. While this will improve performance, it significantly increases complexity as well as capital and operational expenses.

Other organizations are adopting composable infrastructure to more efficiently solve complex problems. Composable infrastructure assigns resources to an application from disaggregated pools of compute storage and networking, as well as GPU, FPGA, and storage accelerators. This approach has yielded results for hyperscalers for some time and is beginning to be adopted by the wider HPC, AI, and machine learning industry. However, it adds bandwidth load on the network because the disaggregated resources must communicate traffic that is also latency sensitive so those resources don't sit idle waiting for a response. This is another scenario that cannot be efficiently managed by traditional centralized switching architectures.

Modern high-performance network architectures are designed to maintain excellent latency and bandwidth performance in multi-workload heterogenous clusters, even when storage traffic is combined with IPC traffic. These network architectures allow a single network to support all cluster traffic without requiring complex tuning and without compromising workload performance. By avoiding centralized switching, modern architectures are also well positioned to better enable the future of composable infrastructure.

5. Ensure Network Resiliency

System availability is an important aspect of architecting a high-performance cluster and, of course, network availability has a huge impact on the ability to access compute and storage resources.

The "blast radius" of a traditional network switch is very significant. In some clusters, 40 to 60 nodes may be connected to the same switch. If that switch fails, none of the compute and storage nodes connected to it can communicate. This can impact dozens of jobs, forcing them to be restarted on other nodes, either from the beginning or from the latest checkpoint — a highly inefficient and disruptive result.

To avoid these inefficiencies, every cluster operator would like to build a redundant interconnect, but the added cost, complexity, power, and rack space make this approach infeasible in most cases. Instead, cluster operators must live with running their workloads on unreliable infrastructure.

> *Modern network architectures have built-in resiliency. In these architectures, the "blast radius" of any failure is limited to a single node.*

This greatly reduces the impact of failures and makes the cluster much more reliable. These same modern architectures also react to link failures within microseconds, ensuring jobs aren't impacted by operational issues.

OBTAINING TELEMETRY DATA FROM THE NETWORK

High-performance cluster architects, operators, and end users have all been frustrated with the lack of information available from their low-latency interconnect network. These networks are like "black boxes" where even static routing information is challenging to obtain.

Network operators using traditional architectures have to query individual switches and manually assemble routes by reading route tables to understand how traffic is flowing through their network. This complexity hampers the ability to troubleshoot almost all aspects of cluster operations, including:

- The root cause of poor network path performance
- Job scaling issues
- Job runtime inconsistencies
- Poorly written HPC code

Modern high-performance network architectures include valuable tooling and management platforms that provide detailed, accurate information about the live and per-job historical state of the network. This includes metrics such as traffic rates, traffic profiles, packet counts, packet size, and general system health for specific cards or ports, as well as network-wide views to highlight trends and outlier activities (Figure 10).

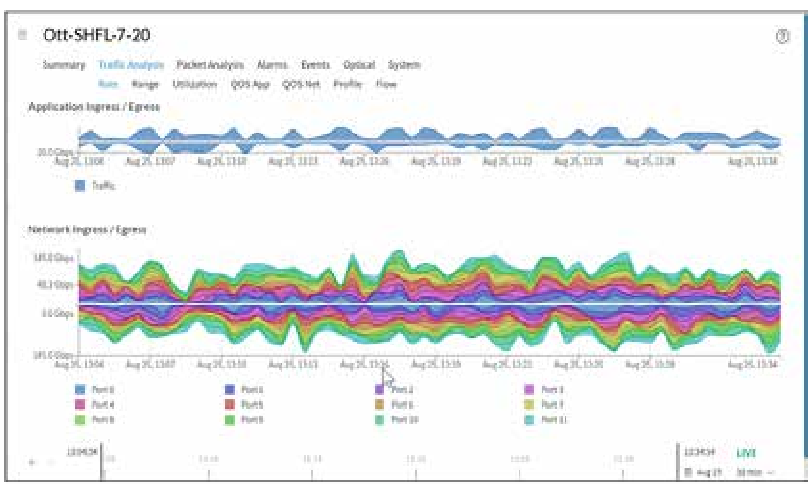
The deep insights available from this data and associated analysis can be used by:

- End users to tune their code to optimize workload performance
- Network operators to gain true understanding of how the network is handlingworkloads
- Network architects to inform decisions about scaling existing clusters anddesigning new clusters

Modern network tools can also identify jobs that are flooding the network with traffic and reducing perfor-mance so network operators can pause or throttle those noisy neighbors, improving performance for all applications, including the bad actor.

Without this information, neither end users nor cluster operators can determine whether a job is running poorly because code needs to be tuned or because the network is causing performance issues.

Figure 10 - Example of Real-Time and Historical Metrics from Modern HPC Networks



6. Test to Accurately Measure Network Performance

In some cases, network operators may suspect there's a performance problem in the network but are unsure how to verify the severity of the issue. In other cases, network operators may not even be aware the network is underperforming.

The first step in measuring network performance is to look for key indications of subpar performance. The next step is to test the network under load to determine how sensitive it is to noisy neighbors and the resulting congestion. These test results highlight the:

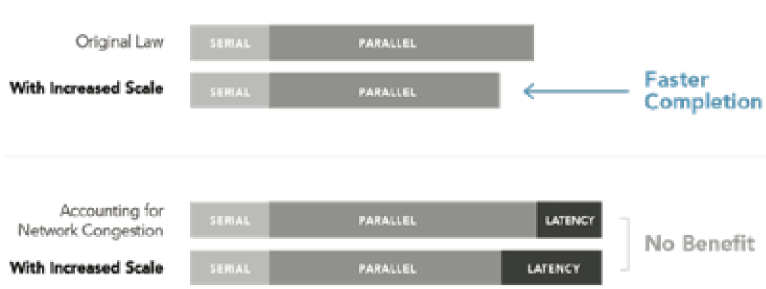
- Precise extent of the performance issue in existing high-performance networks
- Performance improvement when a modern network architecture is introduced

JOB COMPLETION TIMES AND SCALABILITY

One of the major signs of performance problems in traditional networks is variability in job completion times. These variations indicate noisy neighbor issues are present in the network, driving high tail latency that extends job completion times. These delays mean fewer jobs can be completed and jobs are more expensive to run, reducing the overall value the network can deliver.

Another major sign of performance issues is an inability to scale workloads as expected. The problem is related to IPC messages. As HPC workloads are scaled, the massive increase in associated IPC messages makes them more sensitive to latency. Because traditional networks already deliver poor latency performance under load, the added burden of the IPC messages exceeds the gains from the increased parallelism. This outcome aligns with Amdahl's law, which demonstrates that there's a point at which increasing parallelism no longer improves performance (Figure 11).

Figure 11 - Increases in Latency Negate the Effects of Increased Parallelism



TEST PERFORMANCE ON A LOADED NETWORK

> *Testing under load is the only way to accurately verify the performance of traditionally architected and modern networks used for PIC workloads.*

Running network benchmark tests on unloaded networks only provides a baseline, best-case view of network performance. The test results don't account for competing, noisy neighbor traffic, so can't be used to accurately predict network performance in a multi-workload production environment.

Due to the small scale of most test environments, it's typically not possible to run multiple production workloads. To compensate for this fact, well-known traffic generators such as ***ib_send_bw*** and ***iperf*** should be used to generate a realistic network load. These traffic generators provide control over the amount of additional network load, making it possible to predict how gradual increases in noisy neighbor traffic will impact workloads.

For the most accurate test results, the test network should be set up as identically as possible to the production environment. For example, if the production environment uses a two-level spine-and-leaf architecture, the test network should include a minimum of two leaf switches and one spine switch. Similarly, the oversubscription ratio in the test network should match that of the production network.

7. Familiarize Teams with Network Protocols

With some traditional network architectures, architects are challenged to find experienced network operators who can run, maintain, troubleshoot, and tune unfamiliar network protocols. This can be a serious impediment to deploying clusters, growing clusters, and even the ability to run business-critical PIC applications such as HPC, AI, machine learning, deep learning, and high-performance data analytics.

Modern network architectures combine the familiarity of Ethernet — the common language of networking — with the low latency demanded by PIC applications. The benefits of Ethernet-based network architectures for PIC applications are particularly evident in enterprises where Ethernet is the only network protocol familiar to project teams.

A High-Performance Network Architecture for the Future

Modern data- and compute-intensive workloads need a modern network architecture. The switch-intensive network architectures in place today were developed more than 20 years ago, long before the advent of today's highly demanding workloads. As HPC, AI, machine learning, deep learning, and other PIC applications continue to advance, the demands on the network will only increase.

Cerio has designed a modern network architecture that resolves the many performance issues and limitations in traditional InfiniBand and Ethernet switched networks.

The Rockport Switchless Network is modeled after the world's fastest supercomputers. It replaces the traditional centralized switch architecture with a distributed, high-performance direct interconnect architecture that is simple, efficient, and ready for the future. The network is:

- Self-discovering
- Self-configuring
- Self-healing
- Energy efficient
- Easy to deploy and operate
- Interoperable with existing network infrastructures
- Scalable in a cost-effective way

With our modern, direct interconnect network architecture, there are always multiple, physically independent paths through the network. As a result, the network provides high resilience, high throughput, high reliability, and low latency with almost no losses due to congestion. And because it's based on standard Ethernet technology, there are no new protocols to learn.

Learn More

Contact us today to learn more about why switchless networks are essential to support PIC workloads today and tomorrow, and how we can help you get from here to there.

cerio.io/contact

ABOUT CERIO

Cerio, creating new scale economics for the AI and Cloud era, delivers an open systems platform for a more sustainable data center. Built on the foundation of a supercomputing underlay fabric, the Cerio platform provides standards-based, low-code composability services for the cost-effective and efficient management of AI/ML infrastructure.

Formerly Rockport Networks, Cerio is headquartered in Ottawa, Canada, with offices and projects spanning international markets, and Centers of Excellence in Europe and North America.

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