Characterizing and Improving Power and Performance of HPC Networks

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Networks are the backbone of modern HPC systems. They serve as critical infrastructure, tying together applications, analytics, storage and visualization. Despite this importance, we have not fully explored how evolving communication paradigms and network design will impact scientific workloads. As networks expand in the race towards Exascale, a principled approach should be taken to reexamine this relationship so that the HPC community better understands (1) characteristics and trends in HPC communication; (2) how to best design HPC networks to save power or enhance the performance; and (3) how monitoring facilitates scalable, informed, and dynamic decisions within the network. This understanding directly impacts our ability to create efficient Exascale platforms.

**Challenges for HPC communication:** The first challenge is understanding how to best leverage next-generation communication techniques. Traditionally, HPC has followed a bulk synchronous model of communication. That is, large portions of computation followed by mass communication/synchronization. Now, HPC is transitioning towards asynchronous task based paradigms that overlap communication and computation, with fine grain distribution of work across a large number of cores. This overlap between communication and computation can only occur if we can isolate incoming network traffic, so that it does not interrupt the processor responsible for computation. In this respect, Remote direct memory access (RDMA or one-sided communication) provides a convenient mechanism. RDMA allows nodes to largely bypass the CPU of a remote (target) node and read or write directly to a target’s memory, which facilitates computation/communication overlap. This creates new opportunities throughout the HPC ecosystem in areas as diverse as resilience, system monitoring, analytics and visualization. These shifts in communication paradigms require us to reexamine the traditional models of communication and fully explore the impact one-sided communication has on the system.

**Challenges for the network fabric:** Communication paradigms are just a part of the challenges Exascale networks face. Additionally, we must consider the network fabric (the links, routers, switches and NICs). Modern HPC systems require low latency and high bandwidth networks. This demand for performance has forced a steady growth in bandwidth offerings as networks have moved from 54Gb/s in 2011 to a proposed 600Gb/s bandwidth in 2017 [5]. This volume of bandwidth and low latency is necessary due to the bursty traffic patterns common in HPC workloads. For many workloads, it is not uncommon for links to be idle for more 84% of the runtime [10]. If a network is poorly provisioned, these traffic bursts may sporadically create bottlenecks on the fabric that propagate at scale, creating far reaching performance penalties known as system noise [7]. Such a performance penalty is unacceptable, so networks in HPC systems tend to be overprovisioned. This overprovisioning results in increased complexity and monetary costs to the system, and leaves potential for improvement. Furthermore, as we increase the scale of future systems, there is a concern
that these systems will be constrained by power, such that we will not be able to power 100% of the
system at any given time. HPC networks make up a significant portion of total system power. It
takes around 1.7 MW to power the links and network cards in a 100,000 node system [10]. Therefore,
we need to look at how we might temporarily shut down portions of the network to save power when
necessary.

Challenges for monitoring: Any strategy for scaling a network up or down dynamically must
be aware of the workload and the power constraints. This awareness typically involves the use of
large scale system monitoring. Yet, many of the larger HPC systems now span 100,000 nodes or
more. When you consider the hundreds of thousands of switches, NICs, ports and cables operating at
microsecond latencies, monitoring becomes a daunting task. Many of the traditional techniques for
monitoring large systems (e.g. SNMP, OpenSM) are centralized, pull-based approaches that do not
allow for scale or high granularity of collection. Furthermore, because of the propagation of noise,
any monitoring technique must ensure that it does not unduly perturb the system. Even after all of
the raw data has been collected, we have the additional challenge of transforming it into meaningful
insights.

This dissertation explores three topics in HPC networks (1) performance of one-sided communication
and its interaction with the memory subsystem; (2) performance and power tradeoffs for different
dragonfly topologies of Exascale class networks; (3) best practices in monitoring large-scale networks.

Thesis statement I can improve application performance and system power usage by gaining a
detailed understanding of HPC communication on both the network endpoints and fabric; specifically, I
address the problem of network-induced memory contention, quantify the power/performance tradeoffs
for dragonfly topologies in HPC networks, and increase the scalability/responsiveness of large-scale
network monitoring.

This dissertation highlights opportunities for improving network performance and power efficiency,
while uncovering pitfalls (and mitigation strategies) brought about by shifting trends in HPC
communication and fabric design.

At this point we provide a brief overview and contributions of the bodies of work that address
these three topics. Each of these overviews are expanded fully in the proceeding in the referenced
publications.

Evaluating the Performance of Multi-threaded RMA:[6]
On top of lower level communication layers sits libraries such as MPI. Remote Memory Access (RMA)
operations have been incorporated as a part of the MPI-3 specification and it’s important we evaluate
their performance, so that we have a complete understanding of one-sided operations throughout
the communication stack. To this end, we have introduced a set of benchmarks to evaluate the
performance of multi-threaded RMA operations in MPI. These benchmarks are used to both evaluate
and debug Multi-threaded RMA performance within OpenMPI and MVAPICH implementations of
MPI.

Characterizing, Detecting and Eliminating Network-induced Memory Contention:[9]
Communication paradigms are moving towards asynchronous communication mechanisms that pro-
vide opportunities for overlapping communication and computation by bypassing the CPU. We
analyzed the impact this has on creating contention on the memory subsystem and potential solutions
to reduce or avoid the associated performance penalty. Specifically, our results show NiMC can
slowdown application runtime by 3X at scales of 8,192 processes. Our proposed solutions may be
enabled either through changes to hardware or changes in software and can reduce the runtime penalty
to a 0-6% increase (rather than 3X). Furthermore, we explored how we might leverage machine
learning to detect the occurrence of NiMC and predict the degree of performance degradation so
that we may dynamically apply the best solution. Understanding this relationship between RDMA and application performance will be crucial to developing accurate models of network performance in future systems.

Analyzing Large-scale Networks and Characterizing Power and Performance: [10]
The HPC community’s understanding of current and emerging workloads on Exascale network topologies is limited. Left ignored, this naivete will translate into missed opportunities to (1) increase application performance and (2) decrease both power and monetary costs in next generation systems. We used simulation to characterize a variety of relevant workloads on dragonfly topologies of 110,592 nodes. We examined tradeoffs in network design between execution time, power, bandwidth, and the number of global links. Our simulations report stalled, active and idle time on a per-port level of the fabric and we introduce a new method for visualizing network performance. The findings in this work help shape network design decisions in future large-scale networks.

Enabling Scalable Network Monitoring: [8, 11]
Dynamic approaches for saving power and improving performance are reliant on streams of information regarding the current state of the system. For example, these data streams can contain valuable information about the power draw of different components or the utilization of a network link. Understanding the best practices and limitations of system monitoring is an important part of enabling dynamic solutions. With this in mind, we develop scalable push-based approaches for in-network monitoring and introduce a new models for hierarchical data aggregation. We show that we can (1) improve the responsiveness of the monitoring system; (2) accurately predict the cost of data collection with a simple extension to canonical models of parallel computation.

These contributions provide a breadth and depth of a large body of work related to the power and performance of HPC networks. The impact is evident in five peer-reviewed publications [8, 11, 10, 9, 6].
Beyond publications, this work has had direct impact on publicly available software [4, 2, 3, 1], resulting in numerous releases and improvements. As we continue to expand our understanding of HPC systems, it is crucial to have a firm grasp of trends in HPC communications and an understanding of how they impact node-level performance. These models for node level performance must be integrated into a macro level models of network topology, routing and application performance/power constraints. Lastly, in order to implement the dynamic and adaptive solutions that are becoming increasingly common, we must have an understanding of the performance cost associated with network monitoring. Too often these costs remain undiscussed in literature, though they are critical in determining the capabilities of the system. As such, this dissertation sets the stage for a rich body of future work. And though it closes the door on several open research questions, more importantly, it provides the necessary foundation to move forward.

References


