NemC: A Network Emulator for Cluster-of-Clusters

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NemC: A Network Emulator for Cluster-of-Clusters*

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Abstract

A large number of clusters are being used in all different organizations such as universities, laboratories, etc. These clusters are, however, usually independent from each other even in the same organization or building. To provide a single image of such clusters to users and utilize them in an integrated manner, cluster-of-clusters has been suggested. However, since research groups usually do not have the actual backbone networks for cluster-of-clusters, which can be reconfigured with respect to delay, packet loss, etc. as needed, it is not feasible to carry out practical research over realistic environments. Accordingly, the demand for an efficient way to emulate the backbone networks for cluster-of-clusters is overreaching. In this paper, we suggest a novel design for emulating the backbone networks of cluster-of-clusters. The emulator named NemC can support the fine-grained network delay resolution minimizing the additional overheads. The experimental results show that NemC can emulate the low delay and high bandwidth backbone networks more accurately than existing emulators such as NISTNet and NetEm. We also present the performance evaluation results of MPI applications over cluster-of-clusters environment using NemC as a case study, demonstrating the ability of NemC to accurately evaluate the possible benefits for applications executing over cluster-of-clusters environments with varying network characteristics.

Keywords: *Network Emulator, Cluster-of-Clusters, High-Speed Backbone Networks, and MPI*

1. Introduction

Cluster systems are becoming more popular for a wide range of applications owing to their cost-effectiveness. A large number of such clusters are being used in all different organizations such as universities, laboratories, etc. These clusters are, however, usually independent from each other even in the same organization. That is, applications (e.g., scientific parallel applications) can run only on a single cluster and cannot utilize the idle resources of other clusters. Thus it is highly desired that the clusters in the same organization provide a single image to users and are utilized in an integrated manner. As an answer for this requirement, researchers have suggested Cluster-of-Clusters [3, 22], which aims to construct a cluster combining few or many clusters with high-speed backbone networks. Though this term can be also referred as Grid, in this paper, we consider it as a cluster of clusters that geographically distributed in a *small area* (i.e., the same organization or building), which is more tightly coupled system than Grid. This computing environment will be beneficial to the organizations that want to fully utilize their clusters providing a single image without exposing the system to the out side.

The cluster-of-clusters environment poses several research challenges including performance, compatibility, security, authentication, etc. However, before addressing such research challenges, one of the foremost critical issues is how to construct the experimental environment of cluster-of-clusters. Since research groups usually do not have the actual backbone networks for cluster-of-clusters, which can be reconfigured with respect to delay, packet loss, etc. as needed, it is hard to carry out practical research over realistic environments. Accordingly, the demand for an efficient way to emulate the backbone networks for cluster-of-clusters is overreaching. Approaches involving simulations and modeling are widely accepted to achieve this goal [9, 4, 6]; however, this approach has the limitations that it cannot run actual software (i.e., applications, middleware, and system software). On the other hand, if we can emulate only the backbone networks running actual clusters, it will provide more realistic environment for the cluster-of-clusters researches.

Though there are several existing network emulators [7, 12, 18, 19], they are focusing on large scale Wide Area Networks (WANs) such as Internet. However, there are many

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prominently different characteristics between such WANs and the backbone networks for cluster-of-clusters. For example, the backbone networks usually have a much lower delay than typical WAN environments though the backbone networks have a higher delay than the intra-cluster LAN environments. The emulators that can emulate a millisecond network delay resolution may not be enough to emulate the high-seed backbone networks. In addition, the bandwidth provided by the backbone networks for cluster-of-clusters is higher than the WAN case. Hence the emulator should be able to emulate higher bandwidth networks. To reflect the low delay and high bandwidth characteristics, the packet scheduling mechanism of the emulator has to support fine-grained delay resolution with minimum additional overhead. Most of the existing emulators' packet scheduling, however, highly depends on a system timer. If this timer generates interrupts for every or few ticks to support fine-grained delay resolution, its handling would cause a significant overheads. On the other hand, if this timer is slow, it can only support coarse-grained delay resolution. Therefore, we need to design the emulator very carefully to emulate the high-speed backbone networks and this is not a trivial research challenge.

In this paper, we suggest a novel design for emulating the backbone networks of cluster-of-clusters. The emulator named *NemC* (Network Emulator for Cluster-of-Clusters) can support the fine-grained network delay resolution minimizing the additional overheads. We design a new packet scheduling mechanism that performs on-demand scheduling, which is independent on any system timers. Also we minimize the additional overhead by designing it at the kernel-level to emulate high bandwidth networks. In addition to the network delay emulation, current implementation of NemC can emulate packet losses and out-of-order packets. To the best of our knowledge, no research has focused on the network emulation for cluster-of-cluster environments and NemC is the first emulator to address this.

The experimental results show that NemC can emulate the low delay and high bandwidth backbone networks more accurately than existing emulators such as NISTNet [7] and NetEm [12]. We also present the performance evaluation results of MPI [10] applications such as NAS [2] and Gromacs [5] over cluster-of-clusters environment using NemC as a case study. The experimental results reveal that NAS EP can be improved significantly by employing cluster-of-clusters while other applications such as Gromacs d.villin, NAS IS, CG, and FT can perform badly over cluster-of-clusters with high-delay backbone networks.

Rest of this paper is organized as follows: Section 2 briefly overviews the cluster-of-clusters environment and its emulation as a background. Section 3 suggests a new network emulator for cluster-of-clusters and details its design. The experimental evaluation of the emulator and example of its use are presented in Section 4. The related work is discussed in Section 5. Finally, this paper concludes in Section 6.

2. Emulation of Cluster-of-Clusters

To combine the clusters that geographically distributed in a relatively small area and utilize them in an integrated manner, cluster-of-clusters has been suggested. The clusters in a cluster-of-clusters environment are connected through high-speed backbone networks as shown in Figure 1.

The ways to connect different clusters can be categorized into end-node and gateway-based connections. In the end-node based connection, each node has a direct network connection through switch or bridge to the out side of the cluster. In the gateway-based connection, one or more nodes in each cluster are designated as gateway nodes which are connected to the out side of the cluster. The gateway can be also a stand alone network equipment. In this configuration, all inter-cluster communication needs to be first sent to the gateway node which will send the data to the remote cluster. Not only connecting the clusters but also efficient managing the cluster-of-clusters is a research challenge, which includes performance, compatibility, security, authentication, and management policy.

As we have discussed in Section 1, having actual cluster-of-clusters environment is critical but infeasible to most of research groups. Thus the emulation of cluster-of-clusters (especially its backbone networks) is a practical solution, which can provide very close environments to the actual systems but also can give flexibility to change the system parameters, such as network delay, packet loss, etc. For the emulation, a workstation can be configured as a router with multiple Network Interface Cards (NICs), of which each is connected to a cluster through either switch or gateway. By running a network emulation software that generates artificial network delay, packet loss, etc. on the workstation-based router we can emulate the backbone networks for cluster-of-clusters while running actual applications, middleware, and system software over the clusters in a transparent manner. Thus the emulation can open a way to study on actual software running on real clusters while the simulation and modeling cannot provide this.

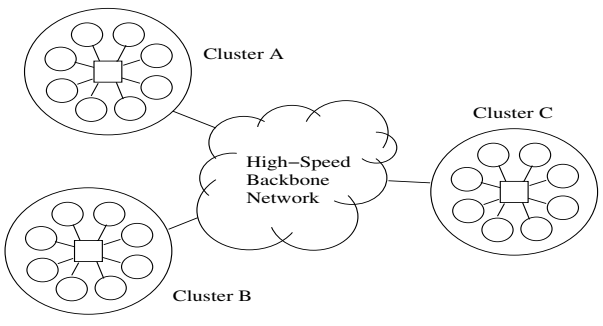


Figure 1. Cluster-of-Clusters Environment

3. Design and Implementation of NemC

In this section, we detail the design and implementation of our network emulator for cluster-of-clusters named NemC. NemC is implemented using the `netfilter` hooks provided by Linux, which can be dynamically inserted to the chain of packet processing by a run-time loadable kernel module, and runs on Linux-based routers. Its design does not require any kernel modifications. The current implementation can generate network delay with fine-grained resolution, packet drops, and out-of-order packets.

Figure 2 shows the overall design of NemC. As shown in the figure, NemC consists of four components: (i) NemC netfilter, (ii) NemC scheduling daemon, (iii) NemC kernel module and (iv) user applications. The NemC netfilter intercepts the packets arrived at the router node after the IP routing decision. Based on the parameters have been set by the user applications the NemC netfilter performs a packet drop, generates out-of-order packet, or introduces network delay. The user applications give the users run-time control over these parameters. The NemC scheduling daemon is a user-level process, which requests the netfilter to search the packets that has been delayed more than desired delay and reinject them into the network. The kernel module takes care of insertion of the netfilter in the initialization phase but also provides access to the internal data structures and parameters of the NemC netfilter to the scheduling daemon and the user applications.

The cluster-of-clusters usually have smaller network delays as compared to typical WANs. Thus it is highly desired that the emulator should emulate the delay with fine-grained resolution. In addition, since the networks between clusters usually support high bandwidth, the emulator needs to be carefully designed to avoid becoming a bottleneck and thereby efficiently emulating high bandwidth networks. In the following subsections we suggest a novel design to tackle these issues.

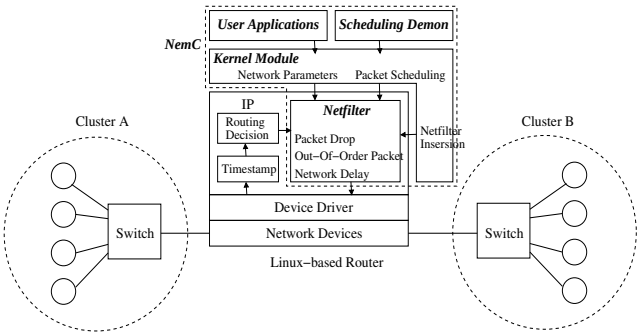


Figure 2. Overall Design of NemC

3.1. Packet Scheduling for Fine-Grained Delay Resolution

The backbone networks for cluster-of-clusters have low network delay compared to general WANs such as Internet. To emulate such networks the emulator is required to support fine-grained delay resolution. The delay resolution of a network emulator is mainly decided by the triggering mechanism of packet scheduling. The packets delayed more than the given time, net_delay, at the router node are reinjected into the network by the packet scheduling routine. The most widely used mechanism to trigger the packet scheduling is to invoke the scheduling routine for every timer interrupt. This mechanism is simple to design and implement; however, since it depends on the system timer resolution, it may not be able to support fine-grained delay resolution. For example, if the network emulator uses Linux timer then it can support only 10ms (with kernel version 2.4) or 1ms (with kernel version 2.6) delay resolution, which is too coarse-grained to emulate the backbone networks for cluster-of-clusters. On the other hand, if the network emulator directly uses a hardware timer in the system, the interrupt can be generated too much frequently and actual packet processing can get delayed.

To overcome these limitations of the timer based mechanism, we suggest the on-demand packet scheduling mechanism. In this mechanism, the packet scheduling routine is triggered by either new arrived packet or scheduling daemon. That is, whenever there is a new packet arrived at the router node, it triggers the packet scheduling routine, while the user-level scheduling daemon keeps on trying to invoke the packet scheduling routine if there is no packets waiting to be processed in the protocol stacks and the system is idle. It is to be noted that the user-level scheduling daemon has lower priority than the kernel-level packet processing context. Thus, if packets arrive at the router node in a bursty manner the scheduling routine will be invoked very frequently by those packets. On the other hand, if packets arrive intermittently then the user-level daemon will continuously trigger the packet scheduling. In this manner, we can trigger the scheduling routine as much as possible (i.e., in a fine-grained mode) without any affection to the actual packet processing of the protocol stacks. In this mechanism, since both newly arrived packets and the user-level daemon invoke the scheduling routine, which accesses the same data structures in the NemC netfilter, we guarantee that only one can access the data structures at a time by locking.

We use the time stamp in the `sk_buff` data structure of the Linux kernel to calculate the total time duration spent by the packet in the router node. Though this time stamp can be set by either NIC's interrupt handler or bottom half, most of current NIC device driver implementations set this field in the interrupt handler. We can also consider to utilize the time stamp in the TCP option header, which is usually used to estimate the round trip time for the TCP congestion control. Since this time stamp has been generated

in the sender side, if we calculate the time difference between sender and emulator node for the connection establishment phase, we can use this value to figure out how long the packet has been stayed in the network. Unfortunately, this time stamp usually has a millisecond resolution. Therefore, this cannot support the desired fine-grained delay resolution. Moreover, only TCP packets include the time stamp value in their header. Thus this mechanism cannot work for other protocol's packets (e.g., UDP packets).

3.2. Low Overhead Emulation for High Bandwidth Support

Another important characteristic of the backbone networks for cluster-of-clusters is high bandwidth. To emulate the high bandwidth networks, we need to address several critical issues, which can be summarized into three: i) delay cascading, ii) emulation overhead, and iii) scheduling priority.

If an emulator holds a packet for a given time to add a delay without yielding the CPU resource, this delay will be cascaded to the next packets that have been already arrived at the router node. For example, if an emulator is implemented as a high priority kernel-level process and polls the timer occupying the CPU resource, the delay can be cascaded to the next packets. To avoid this delay cascading problem, we queue the packets that need to be delayed into a doubly linked list and immediately return the context to the original routine. The packets queued are re-injected by the packet scheduling mechanism described in Section 3.1.

If the overhead involved in the network emulation is significant, the emulator reduces the bandwidth between the clusters in the experimental systems, which is a undesired side effect. Broadly, the emulator can be implemented at the user-level or the kernel-level. The user-level emulation requires two data copies between user and kernel buffers for each packet. This copy operation is a well-known bottleneck of packet processing [13]. Hence, our network emulator is designed at the kernel-level to prevent any additional data copy.

Due to the high bandwidth link of the backbone networks, the packet arrival rate can be drastically high. Thus it is important that the actual packet processing in the protocol stacks has to be retained without affection by the emulator. Otherwise, the packet processing gets delayed, packets are accumulated in the router node, and following packets are dropped due to the lack of system resources (e.g., memory). It is to be noted that this drop is not intended by the emulator for the purpose of network emulation. To prevent this packet drop, we assign a lower priority to the scheduling daemon than the actual packet processing routines. In this case, though the scheduling daemon may not invoke the packet scheduling in time, we still can trigger the packet scheduling and satisfy the requirement for the fine-grained delay resolution because newly arrived packets also invoke the packet scheduling as described in Section 3.1.

3.3. Packet Drop

Since the backbone networks for cluster-of-clusters can use store-and-forward networks also there can be packet drops because of network congestion. To emulate such case, we generate packet drops based on the packet drop rate value, $drop\_rate$, given by a NemC user application. NemC chooses a packet randomly for every $drop\_rate$ packets and simply drops this packet freeing all the resources occupied by this packet.

3.4. Out-of-Order Packet Generation

Out-of-order packets can occur in cluster-of-clusters due to multi-path and adaptive routing. To emulate such case, we generate out-of-order packets using a given out-of-order packet generation rate, ooo_rate, and a delay for out-of-order packets, ooo_delay. These values are set by a NemC user application. It is guaranteed that the value of ooo_delay is always larger than that of net_delay. NemC chooses a packet randomly for every ooo_rate packets and delays this packet as much as ooo_delay. Since this packet has been delayed more than other packets it becomes an out-of-order packet if the packet interval between this packet and the next is smaller than ooo_delay.

4. Experimental Evaluation of NemC

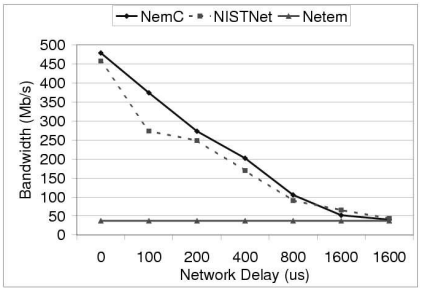
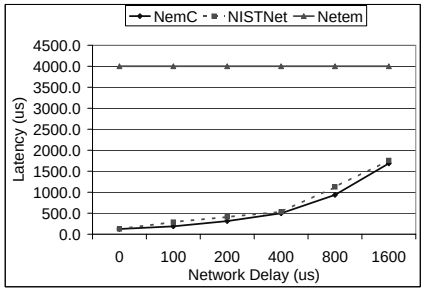


Figure 4. Performance Comparison of Bandwidth with Varying Network Delay

In this section, we describe our experimental methodology. We provide the details of our testbed in Section 4.1. Section 4.2 compares our network emulator NemC with popular existing network emulators and evaluates the benefits of NemC. In Section 4.3, we outline the overall usage of NemC and we demonstrate the main uses of NemC. Since it was difficult to connect our clusters through a real backbone network, in this paper we could not compare the emulated results with real results. We intend to show the comparison in future work.



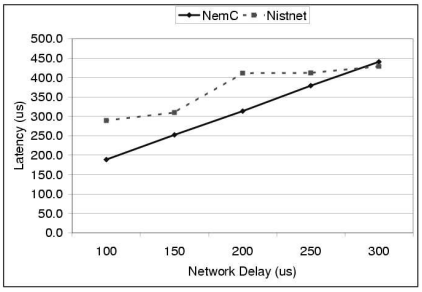
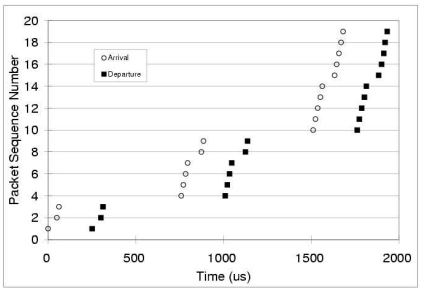


Figure 3. Latency: (a) Comparison with Varying Network Delay (b) Fine-Grained Network Delay



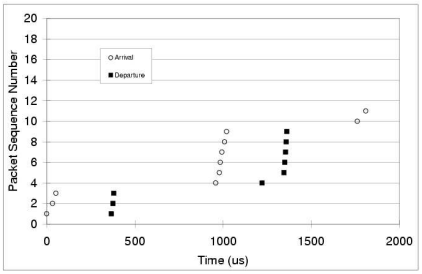


Figure 5. TCP Flow Analysis for (a) NemC and (b) NISTNet

4.1. Experimental Testbed

For all our experiments we used two clusters whose descriptions are as follows:

Cluster A: A cluster system consisting of 4 nodes built around SuperMicro SUPER P4DL6 motherboards and GC chipsets which include 64-bit 133 MHz PCI-X interfaces. Each node has two Intel Xeon 2.4 GHz processors with a 512 KB L2 cache and a 400 MHz front side bus and 512 MB of main memory. We used the RedHat 9.0 Linux distribution.

Cluster B: A cluster system consisting of 4 nodes built around SuperMicro SUPER X5DL8-GG motherboards with ServerWorks GC LE chipsets which include 64-bit 133 MHz PCI-X interfaces. Each node has two Intel Xeon 3.0 GHz processors with a 512 KB L2 cache and a 533 MHz front side bus and 512 MB of main memory. We used the RedHat 9.0 Linux distribution.

The nodes are connected with Ammasso Gigabit Ethernet interface cards. The software (SDK) version used is 1.2-ga2. These cluster nodes are internally connected with Netgear GS524T Gigabit Switches. As shown in Figure 2 these switches are connected each other through the workstation-based router that is similar in configuration to Cluster B nodes'. This router node runs NemC to emulate the backbone networks.

Latency is and bandwidth is measured using the `nttcp` Version-1.47. We have used the MPI [10] library MPICH Version 1.2.7p1 [11] for our application level case study. Gromacs Version 3.3 [5] and NAS Version 2.3 [2] are used for MPI applications.

4.2. Microbenchmarks

In this section, we compare NemC with existing emulators such as NISTNet [7] and NetEm [12]. We measure the latency and the bandwidth with `nttcp` varying the emulated network delay. Since the focus of the paper is the fine-grained network delay emulation for cluster-of-clusters we do not include the experimental results for packet drop and out-of-order packet cases.

Figure 3(a) shows the 512B message latency between two nodes in different clusters, Clusters A and B, while emulating the network delay using NemC, NISTNet, and NetEm. We vary the network delay from 0μs to 1600μs. As we can see in the figure, NetEm shows almost constant latency regardless of the expected network delay. Also this latency is much higher than the given delay. It is because the packet scheduling of NetEm uses the Linux system timer, which has milliseconds timer resolution. Hence, it cannot generate the fine-grained network delay. On the other hand, NemC and NISTNet generate the network delay very close to the given delay value.

To closely look at NemC and NISTNet, we measure the

512B message latency again with finer network delay values. Figure 3(b) presents the results. We can observe that NISTNet shows interestingly the almost same latency for 100μs and 150μs delay values. We can observe the same trend with 200μs, 250μs, and 300μs delay values. It is due to the fact that NISTNet uses the MC146818 real-time clock for the packet scheduling of which the tick resolution is approximately 122μs. Therefore, it cannot support finer network delay resolution than 122μs. On the other hand, as we can see in the figure, NemC is emulating the given delay values accurately. The reason why we see around 200μs latency with 100μs network delay is because of the default latency between two nodes, which is roughly 100μs.

Figure 4 shows the 512B message bandwidth results between two nodes in different clusters while emulating the network delay using NemC, NISTNet, and NetEm. Similarly to the latency results, NetEm shows almost the same bandwidth no matter what delay value has been given. Since NetEm adds to much delay for small delay values the bandwidth is also very low. More importantly, we can observe that NemC can achieve higher bandwidth (up to 37%) than NISTNet for small network delay values. The reason why the bandwidth of NemC and NISTNet drops with larger network delay is that the maximum TCP window size set to 512KB during the test cannot fill the network pipe of which size increases as the network delay becomes larger. To compare NemC and NISTNet in detail, we execute `tcpdump` on the router node, in which the emulator is running, and observe the behavior of each emulator while performing the bandwidth test. For this experiment, we have set the network delay into 250μs. The message size is 512B. Figures 5(a) and (b) present a snapshot for 0 to 2ms of NemC and NISTNet, respectively. The graphs show when each packet has been arrived at the router node (indicated with empty circles in the figures) and when it has left (plotted with filled rectangles in the figures). With these figures we can clearly see how long the packets have been delayed in the router node by the emulator. As we can observe in the figure, NemC emulates 250μs network delay very accurately while NISTNet adds more than 350μs, which is 40% error. This is why we see better bandwidth with NemC than NISTNet in Figure 4.

4.3. Case Study: MPI Applications over Cluster-of-Clusters

In this section, we evaluate and analyze the performance of MPI applications over cluster-of-clusters using our network emulator, NemC. Further, we study the trends shown by various applications running over cluster-of-clusters with different delay characteristics. We choose the the following applications as a representative set for evaluation: (i) NAS (Class B)- EP, IS, MG, CG and FT and (ii) Gromacs - d.villin.

Each evaluation is divided into two parts: (i) Execution on a single cluster (represented by 4x1 in the graphs) and (ii) execution on a cluster-of-clusters with varying emulated network delay (represented by the corresponding network delay in the graphs). Each single cluster contains 4 nodes. The cluster-of-cluster experiments utilize the nodes of both the clusters. These are connected as described earlier in Section 4.1.

Figure 6(a) shows the performance of EP. The single cluster execution of EP takes 82.5s. Further, we notice that the execution times of EP over a cluster-of-cluster do not depend largely on the network delay. Based on this observation we conclude that the network communication required by this application is very low and that the application is primarily CPU bound. Performance and Execution time of applications like EP can hence be improved immensely by utilizing the nodes of cluster-of-clusters. In addition, since the network delay does not effect the execution time of EP executed on cluster-of-clusters significantly, these applications can benefit even from cluster-of-clusters formed by widely separated clusters with high network delay.

In Figure 6(b), we observe that the network delay shows a fair impact on the execution times of IS and MG. The execution times of these applications executed on single clusters (50.3s and 24.4s respectively) are higher than the their execution times with well-connected cluster-of-clusters (about 30.0s and 16.4s respectively for network delay of 100μs). This shows that these applications can perform up to 67% and 48% faster using the cluster-of-cluster setup. Further, we notice that the benefit of using cluster-of-clusters diminishes with increasing network delay. Hence these applications can benefit from running on multiple clusters for network delays up to some extent. Figure 7(a) shows the applications CG and FT that follow similar execution trends.

Performance of Gromacs - d.villin shown in Figure 7(b) shows that the single cluster execution of this application performs significantly better than its execution on cluster-of-clusters (with all delays). It is to be noted that the y-axis of this graph is *Simulations/Day*. Since this application is highly communication intensive, the execution on more number of nodes spread over the high delay networks increase its communication overheads heavily. Hence applications like these can rarely benefit from cluster-of-cluster systems.

In aggregate, we have demonstrated that our network emulator NemC can accurately answer the following: (i) Can a given application execute faster on a cluster-of-cluster? (ii) What is the maximum network delay that can sustain this benefit? and (iii) What is the measure of the extent of benefit possible? The capability of NemC to emulate fine-grained delay enables us to evaluate and predict these trends accurately.

5. Related Work

There have been several researches for network emulation. NISTNet [7] and NetEm [12] are the widely em-

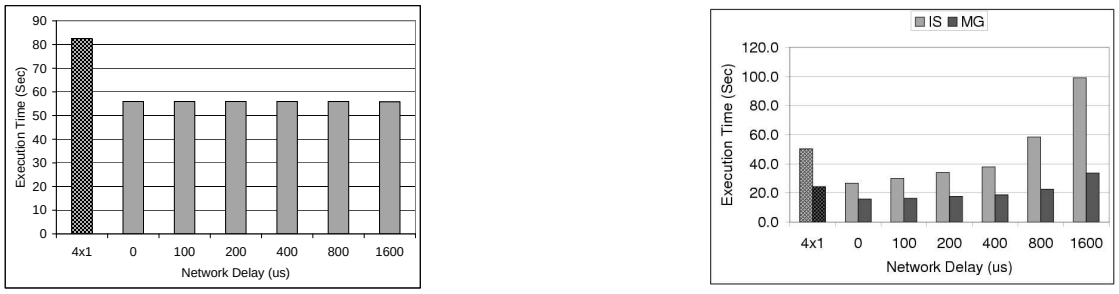


Figure 6. Performance of MPI Applications - *Single Cluster* Vs *Cluster-of-Clusters* (a) NAS - EP and (b) NAS - IS, MG

Figure 7. Performance of MPI Applications -*Single Cluster* Vs *Cluster-of-Clusters* (a) NAS - CG, FT and (b) Gromacs - d.villin

ployed network emulators running on Linux systems. However, these emulators are focusing on how to emulate general WANs. Hence fine-grained network delay resolution was not an important factor to these emulators as shown in Section 4.2. On the other hand, NemC has been designed carefully to deal with low delay and high bandwidth network characteristics of cluster-of-clusters. For FreeBSD based systems, Dummynet [18] and ModelNet [19] have been suggested. Again, these emulators target large scale WANs rather than cluster-of-clusters environment.

There are also well designed Grid emulators. For example, MicroGrid [16] provides a virtual Grid environment for Grid applications. Netbed [21] provides integrated access to simulated, emulated, and wide-area network testbeds. These emulators are very beneficial to develop and evaluate applications over large scale Grid environments.

In addition, there are several wireless network emulators. ONE [1] is a satellite communication emulator running on Solaris. MOST Emulator [8], Ntrace [17], and Mobile Emulab [15] are also examples of mobile network emulators. Since mobile networks have different characteristics with the high-speed backbone networks for cluster-of-clusters, such emulators are not suitable for the emulation of cluster-of-clusters environment.

We also have introduced a simple delay generator for network emulation in one of our previous works to evaluate RDMA over IP [14]. This emulator, however, does not consider all the design issues discussed in this paper and has only limited features.

6. Conclusions and Future Work

In this paper, we suggest a novel design for emulating the backbone networks of cluster-of-clusters. The emulator named NemC can support the fine-grained network delay resolution minimizing the additional overheads. To reflect the low delay and high bandwidth characteristics of the backbone networks, we design a new packet scheduling mechanism that performs on-demand scheduling, which is independent on any system timers. Also we minimize the additional overhead by designing it at the kernel-level to emulate high bandwidth networks. In addition to the network delay emulation, current NemC implementation can emulate packet losses and out-of-order packets.

The experimental results clearly show that NemC can emulate the low delay and high bandwidth backbone net-

works more accurately than existing emulators such as NISTNet and NetEm. We also present the performance evaluation results of MPI applications such as NAS and Gromacs over cluster-of-clusters environment using NemC as a case study. The experimental results reveal that applications like NAS EP can be improved significantly by utilizing cluster-of-clusters. Other applications such as NAS IS, MG, CG, and FT can show worse performance over cluster-of-clusters for high-delay backbone networks. Among these applications, we also notice that NAS MG shows less sensitivity on the network delay as compared to other applications (i.e., IS, CG, and FT). Performance of Gromacs - d.villin shows that the single cluster execution of this application performs significantly better than its execution on cluster-of-clusters. On the whole, we demonstrate the ability of NemC to accurately evaluate the possible benefits (or lack thereof) for applications executing over cluster-of-clusters environments with varying network characteristics.

As future work, we plan to add more features such as generating duplicated packets and statistical generation of delay. In addition, we intend to evaluate NemC with 10 Gigabit Ethernet [20]. We also plan to evaluate the applications over a larger system size and compare with real backbone network results.

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