Deep Learning Performance Comparing Scale-out vs Scale-up

Abstract
This whitepaper looks at the performance and efficiency of Deep Learning training when using the Dell EMC PowerEdge C4140 server to run neural models. The objective is to show how the C4140 in scale-out configuration performs against scale-up server.

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# Deep Learning Performance: Scale-up vs Scale-out

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- Nimbix engineering and support team.


1 Overview

The objective of this whitepaper is to compare Dell’s PowerEdge acceleration optimized servers and determine their performance when running deep learning workloads. The purpose is to highlight how Dell’s scale out solution is ideally suited for these emerging workloads.

We will compare how PowerEdge C4140 performs using one of the more popular frameworks like TensorFlow with various neural architectures and compare it to other acceleration optimized servers in the market, targeting the same workloads. The idea is to investigate whether the architectural implementation helps PowerEdge C4140 in better utilizing the accelerators when running hardware level benchmarks like Baidu Deep bench and TensorFlow based benchmarks.

Using Baidu Deep bench, we can profile kernel operations, the lowest-level compute and communication primitives for Deep Learning (DL) applications. This allows us to profile how the accelerators are performing at the component level in different server systems. This is very important since it allows us to look at which hardware provides the best performance on the basic operations used for deep neural networks. Deep Bench includes operations and workloads that are important to both training and inference.

Using TensorFlow as the primary framework, we compare the performance in terms of throughput, and training time to achieve certain accuracy on ImageNet dataset. We look at performance at a single node level and multi-node level. We use some of the popular neural architectures like ResNet-50, VGG Net, GoogLeNet, and AlexNet to do this performance comparison.

1.1 Definition

**Scale up**: Scale up is achieved by putting the workload on a bigger, more powerful server (e.g., migrating from a two-socket server to a four- or eight-socket x86 server in a rack-based or blade form factor). This is a common way to scale databases and several other workloads. It has the advantage of allowing organizations to avoid making significant changes to the workload; IT managers can just install the workload on a bigger box and keep running it the way they always have.

**Scale out**: Scale out refers to expanding to multiple servers rather than a single bigger server. The use of availability and clustering software (ACS) and its server node management, which enables IT managers to move workloads from one server to another or to combine them into a single computing resource, represents a prime example of scale out. It adds flexibility in allowing IT organizations to add nodes as the number of users or workloads increase and this helps in better control of IT budgets.
2 Introduction

Artificial Intelligence

First coined in 1956 by John McCarthy, **Artificial Intelligence involves machines that can perform tasks that are characteristic of human intelligence.** While this is rather general, it includes things like planning, understanding language, recognizing objects and sounds, learning, and problem solving.

Machine Learning

Arthur Samuel coined the phrase not too long after AI, in 1959, defining it as, “the ability to learn without being explicitly programmed.” You see, you can get **AI without using machine learning**, but this would require building millions of lines of codes with complex rules and decision-trees.

So instead of hard coding software routines with specific instructions to accomplish a task, **machine learning is a way of “training” an algorithm so that it can learn how.** “Training” involves feeding massive amounts of data to the algorithm and allowing the algorithm to adjust itself and improve.

Spiking Neural Networks

**Spiking neural networks (SNNs)** are artificial neural network models that more closely mimic natural neural networks. In addition to neuronal and synaptic state, SNNs also incorporate the concept of time into their operating model. The idea is that neurons in the SNN do not fire at each propagation cycle (as it happens with typical multi-layer perceptron networks), but rather fire only when a membrane potential – an intrinsic quality of the neuron related to its membrane...
electrical charge – reaches a specific value. When a neuron fires, it generates a signal which travels to other neurons which, in turn, increase or decrease their potentials in accordance with this signal.

2.1 Deep Learning
Deep Learning consists of two phases: Training and inference. As illustrated in Figure 2, training involves learning a neural network model from a given training dataset over a certain number of training iterations and loss function. The output of this phase, the learned model, is then used in the inference phase to speculate on new data [1].

The major difference between training and inference is training employs forward propagation and backward propagation (two classes of the deep learning process) whereas inference mostly consists of forward propagation. To generate models with good accuracy, the training phase involves several training iterations and substantial training data samples, thus requiring many-core CPUs or GPUs to accelerate performance.

![Figure 2. Deep Learning phases](image)

3 Background
With the recent advances in the field of Machine Learning and especially Deep Learning, it’s becoming more and more important to figure out the right set of tools that will meet some of the performance characteristics for these workloads.

Since Deep Learning is compute intensive, the use of accelerators like GPU become the norm. But GPUs are costly and often it comes down to what is the performance difference between a system with & without GPU.
The plot in Figure 3 shows GPU performance when looking at single precision and Figure 4 shows GPU performance when looking at half-precision. Most of the Deep Learning frameworks and models take advantage of half-precision since they can work with larger datasets with the available memory. It’s very important to look at the raw Flop numbers for a GPU, since we want to extract the same level of performance when that GPU is put into a system.

Figure 3 NVidia GPU Performance - Single precision [7]
In order to see whether Dell EMC PowerEdge servers can meet the raw Flop numbers indicated in the charts above, we approached the problem by breaking it up into different sections. The picture below better illustrates how we are approaching this testing.

Figure 5: Machine Learning Stack

1. Hardware
   - Finally, the models are trained on hardware like NVIDIA GPUs, Intel’s Xeon Phi processor or other specialized processors.

2. Neural network Libraries
   - cuDNN, cuBLAS, MKL, NCCL...
   - In order to train the deep learning models, the frameworks work with underlying neural network libraries such as NVIDIA’s cuDNN and Intel’s MKL. These libraries implement operations such as matrix multiply that are important to deep learning models.

3. Deep Learning Frameworks
   - TensorFlow, MXNet, CNTK, Chainer, Theano...
   - All these frameworks allow deep learning researchers to build models. They include basic building blocks like layers which can be connected in different ways to create a model.

4. Neural Network API
   - Keras, Lasagne, Blocks
   - These are top level API which mostly support TensorFlow and Theano as the backend. Their advantage is ease of use.
1. System bandwidth performance i.e. PCIe connected to GPU - p2p bandwidth & latency tests
2. GPU hardware performance without any Deep learning frameworks – Baidu Deep Bench

3.1 Criteria
1. In order to bound our testing, we picked TensorFlow as the framework of choice since it has better support and models are readily available.
2. For distributed training, we selected Uber Horovod implementation, since it’s one of the best performing distributed implementation [2].

3.2 Why TensorFlow as the framework of choice?
The reason we selected TensorFlow is because it’s the most widely used framework of choice for machine learning and deep learning. It also has a wider support within open source community and availability of pre-trained models. It also has better community support and supported very well by the TensorFlow team.

TensorFlow is also widely used within the Dell EMC customer base and one of the top choices when developing any new projects in machine learning. Figure 6 shows how TensorFlow compares in terms of GitHub commits, stars and number of forks. This is a pretty good indicator of its widespread adoption.
4 Test Methodology

The test methodology consists of 3 distinct phases.

Phase 1 is where we test the hardware performance of each server using NVidia supplied p2pbandwidth and latency tests and Baidu Deep Bench. This is explained in section Phase 1.

Phase 2 we used TensorFlow framework and ran some of the well-known neural models to compare performance in terms of throughput & training time. This is explained in section Phase 2.

Phase 3 we used TensorFlow but compared performance at multi-node level using Uber’s Horovod implementation.
Figure 7: Testing Methodology Workflow

1) **Phase 1** – In this phase we are performing some of the basic tests like PCIe bandwidth and latency tests to ensure it aligns to what we expect based on theoretical numbers. We then ran Baidu Deep Bench Benchmarks to evaluate deep learning performance for the accelerators and the system. The results for this step are presented in a separate whitepaper.

2) **Phase 2** - We used the official TensorFlow benchmarks which were run across several servers.

3) **Phase 3** – To benchmarks the servers in the distributed mode we used Horovod, which is a distributed training framework for TensorFlow.

### 4.1 Testing Methodology

We cover the testing methodology for Phase 1 in detail with its results in a separate whitepaper. Here we will describe the methodology we used in Phase 2 and Phase 3.

To establish a baseline, we divided it into short tests and long tests.

#### 4.1.1 Short Test

The short tests consisted of 10 warmup steps and then another for another 100 steps which were averaged to get the actual throughput. The benchmarks were run with 1 GPU to establish a baseline number of images/sec and then increasing the number of GPUs under test based on the number of GPUs supported.
4.1.2 Long Test
The long tests were run to get throughput and the training time to reach certain accuracy convergence. We used 90 epochs for training run. These tests were run using the maximum number of GPUs supported by that server.

In the section below, we describe the setup used, and Table 1 gives an overall view on the test configuration.

- **Use Case** – The benchmark tests are targeting image classification with convolutional neural networks models (CNNs).
- **Benchmark code** – TensorFlow Benchmarks scripts
- **Hardware Configuration** – Each server is configured based on its maximum GPU support.
- **Servers** - The servers tested are PowerEdge R740, PowerEdge C4130, PowerEdge C4140 and non-Dell EMC 8x NVLink GPU server.
- **Frameworks** – TensorFlow for single node, and TensorFlow with Horovod library for distributed training.
- **Performance** – The performance metrics used for comparison across servers is throughput (images per second) and training time to reach top-5 accuracy and top-1 accuracy.
- **Training tests** - We conducted two types of tests. 1- Short Tests: for each test, 10 warmup steps were done and then the next 100 steps were averaged. 2-Long Tests: to get the training accuracy convergence, and elapsed training time.
- **Dataset** – ILSVRC2012
- **Software stack configuration** – The benchmarks were run under docker container environment. See table 1 with details.

4.2 Throughput Testing

<table>
<thead>
<tr>
<th>Workload application and model</th>
<th>Image classification with convolutional neural networks models (CNNs)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Benchmarks code</strong></td>
<td>TensorFlow Benchmarks scripts</td>
</tr>
<tr>
<td><strong>Server</strong></td>
<td><strong>GPU</strong></td>
</tr>
<tr>
<td><strong>Servers – Single Node</strong></td>
<td><strong>PowerEdge R740</strong></td>
</tr>
<tr>
<td></td>
<td><strong>PowerEdge C4140</strong></td>
</tr>
<tr>
<td></td>
<td><strong>PowerEdge C4140</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Non Dell EMC 8x NVLink server</strong></td>
</tr>
<tr>
<td><strong>Servers – Multi Node</strong></td>
<td><strong>PowerEdge C4140-K</strong></td>
</tr>
<tr>
<td>(2 nodes, 4GPUs each)</td>
<td><strong>PowerEdge C4140-K</strong></td>
</tr>
<tr>
<td></td>
<td><strong>PowerEdge C4140-M</strong></td>
</tr>
<tr>
<td><strong>Frameworks</strong></td>
<td><strong>TensorFlow for Single Mode</strong></td>
</tr>
<tr>
<td></td>
<td><strong>TensorFlow with Horovod library for Distributed Mode</strong></td>
</tr>
</tbody>
</table>
Deep Learning Performance: Scale-up vs Scale-out

| Performance Metrics       | • Throughput images/second  
|                          | • Top-5 Accuracy on the training dataset  
|                          | • Training time  |
| Training Tests           | • Short Tests to get throughput images/second  
|                          | • Long Tests to get accuracy convergence and training time  |
| Dataset                  | ILSVRC2012  |

Table 1: Benchmark Setup

4.3 Neural Models & parameters

<table>
<thead>
<tr>
<th>Models</th>
<th>Short Tests</th>
<th>Long Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Models</td>
<td>• VGG-16</td>
<td>• VGG-19</td>
</tr>
<tr>
<td></td>
<td>• VGG-19</td>
<td>• Inception-v4</td>
</tr>
<tr>
<td></td>
<td>• Inception-v3</td>
<td>• ResNet50</td>
</tr>
<tr>
<td></td>
<td>• Inception-v4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• ResNet50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• GoogLeNet</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• AlexNet</td>
<td></td>
</tr>
</tbody>
</table>

| Batch sizes     | 32                               | 32                               |
|                 | 64                               | 64                               |
|                 | 128                              | 128                              |
|                 | 256                              | 256                              |
|                 | 512                              |                                  |
|                 | 2014                             |                                  |
|                 | 2048                             |                                  |

| GPUs            | 1                                | 3                                |
|                 | 2                                | 4                                |
|                 | 3                                |                                  |
|                 | 4                                |                                  |
|                 | 5                                |                                  |
|                 | 6                                |                                  |
|                 | 7                                |                                  |
|                 | 8                                |                                  |

| Training Steps or Epochs | 100 steps                  | 90 epochs                  |

Table 2: Neural Models & Parameters
5  PowerEdge Server Details

5.1  PowerEdge C4140

The Dell EMC **PowerEdge C4140**, an accelerator-optimized, high density 1U rack server, is used as the compute node unit in this solution. The PowerEdge C4140 can support four NVIDIA Volta SMX2 GPUs, both the V100-SXM2 as well as the V100-PCle models.

Dell EMC PowerEdge C4140 supporting NVIDIA Volta SXM2 in topology ‘M’ with a high bandwidth host to GPU communication is one of the most advantageous topologies for deep learning. Most of the competitive systems supporting either a 4-way or 8-way or 16-way NVIDIA Volta SXM use PCIe bridges and this limits the total available bandwidth between CPU to GPU.

5.1.1  Why is C4140 Configuration-M better?

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Link Interface b/n CPU- GPU complex</th>
<th>Total Bandwidth</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>X16 Gen3</td>
<td>32GB/s</td>
<td>Since there is a PCIe switch between host to GPU complex</td>
</tr>
<tr>
<td>G</td>
<td>X16 Gen3</td>
<td>32GB/s</td>
<td>Since there is a PCIe switch between host to GPU complex</td>
</tr>
<tr>
<td>M</td>
<td>4x16 Gen3</td>
<td>128GB/s</td>
<td>Each GPU has individual x16 Gen3 to Host CPU</td>
</tr>
</tbody>
</table>

Table 3: Host-GPU Complex PCIe Bandwidth comparison

As shown in Table 3 the total available bandwidth between CPU – GPU complex is much higher than other configurations. This greatly benefits neural models in taking advantage of larger capacity although lower bandwidth DDR memory to speed up learning.

*Figure 8* shows the CPU-GPU and GPU-GPU connection topology for C4140-K, *Figure 9* shows topology for C4140-M and *Figure 10* shows topology for C4140-B.
Deep Learning Performance: Scale-up vs Scale-out

Configuration K

Figure 8: C4140 Configuration-K

NVLKink

PCIe
Configuration M

Figure 9: C4140 Configuration-M

NVLink

PCIe
5.2 PowerEdge R740/R740xd
The PowerEdge R740/R740xd is a general-purpose platform with highly expandable memory (up to 3TB) and impressive I/O capability to match both read-intensive and write-intensive operations. The R740 is capable of handling demanding workloads and applications such as data warehouses, E-commerce, databases, high-performance computing (HPC), and Deep learning workloads.

Figure 11 below shows the topology connection for CPU: GPU in PowerEdge R740/R740xd server.
6  Framework Setup Details
6.1  Distributed Horovod-TensorFlow Setup

Horovod [8] [9] [10] is a distributed training framework for TensorFlow, Keras and PyTorch initially developed by Uber. It uses bandwidth-optimal communication protocols (RDMA) [2].

In this section, we explain briefly the software stack configuration we used to extract the performance throughput in multi-node using distributed Horovod TensorFlow and using high speed Mellanox InfiniBand ConnectX-5 network adapter with 100Gbit/s over IPoIB, and GPUDirect RDMA.

To setup the configuration, we used as our reference the configuration procedure presented by Mellanox on its community blog space [3] and the basic installation of Horovod in Docker [4].
The tests were run in docker environment, *Figure 12* shows the different logical layers involved in the software stack configuration. Each server is connected to the InfiniBand switch; has installed on the Host the Mellanox OFED for Ubuntu, the Docker CE, and the GPUDirect RDMA API; and the container image that was built with Horovod and Mellanox OFED among other supporting libraries. To build the extended container image, we used the Horovod docker file and modified it by adding the installation for Mellanox OFED drivers.

In *Figure 13* below shows how PowerEdge C4130/C4140 is connected via InfiniBand fabric for multi-node testing.
In Figure 14 we see how the GPU memory is accessed directly instead of copying the data n times across the system components with the use of GPUDirect RDMA, this feature is reflected directly in the throughput performance of the server.

![Nvidia GPU Direct RDMA Connection](https://www.sc-asia.org)

**Figure 14**: Nvidia GPU Direct RDMA Connection. Source: https://www.sc-asia.org

### 6.2 Evaluation Platform Setup

Table 4 shows the software stack configuration used to build the environment to run the tests.

<table>
<thead>
<tr>
<th>Software Stack</th>
<th>PowerEdge Servers</th>
<th>Non-Dell EMC Servers</th>
</tr>
</thead>
<tbody>
<tr>
<td>OS</td>
<td>Ubuntu 16.04.4 LTS</td>
<td>Ubuntu 16.04.3 LTS</td>
</tr>
<tr>
<td>Kernel</td>
<td>GNU/Linux 4.4.0-128-generic x86_64</td>
<td>GNU/Linux 4.4.0-130-generic x86_64</td>
</tr>
<tr>
<td>nvidia driver</td>
<td>396.26 for all servers</td>
<td>384.145</td>
</tr>
<tr>
<td></td>
<td>390.46 for R740-P40</td>
<td></td>
</tr>
<tr>
<td>Open MPI</td>
<td>3.0.1</td>
<td>3.0.0</td>
</tr>
<tr>
<td>CUDA</td>
<td>9.1.85</td>
<td>9.0.176</td>
</tr>
<tr>
<td>cuDNN</td>
<td>7.1.3.16</td>
<td>7.1.4</td>
</tr>
<tr>
<td>NCCL</td>
<td>2.2.15</td>
<td>2.2.13</td>
</tr>
<tr>
<td>Docker Container</td>
<td>NVidia TensorFlow Docker</td>
<td>Nvidia TensorFlow Docker</td>
</tr>
<tr>
<td>Container Image – Multi Node</td>
<td>Horovod : latest</td>
<td>n/a</td>
</tr>
<tr>
<td>Benchmark scripts</td>
<td>tf_cnn_benchmarks</td>
<td>tf_cnn_benchmarks</td>
</tr>
<tr>
<td>Test Date – V1</td>
<td>April–June 2018</td>
<td>July 2018</td>
</tr>
<tr>
<td>Test Date - V2</td>
<td>Jan 2019</td>
<td>NA</td>
</tr>
</tbody>
</table>

**Table 4**: OS & Driver Configurations
7 Performance Results

7.1 Single Node – Throughput (images/sec)

The charts below show the results for different servers running the short tests to extract throughput images/second using ResNet50 with batch size 128 and number of steps =100.

The results for single node are with maximum number of GPUs supported within that node.

7.1.1 PowerEdge R740xd

![PowerEdge R740-P40 server with up to 3 GPUs](image)

The PowerEdge R740 with P40 GPU is tested with different pre-trained neural models. The results show how different models use the amount of available memory e.g. ResNet50 uses more memory than GoogLeNet or AlexNet and therefore we see lower throughput.
7.1.2 PowerEdge C4140-V100-16GB-PCIe [Config B] – Single Node

![PowerEdge C4140-V100-16GB-PCIe - CNN Performance (images/second) Single Node (1, 2, 3 and 4 GPUs)](image1)

Figure 16: PowerEdge C4130-P100-16GB-PCIe in single-node

7.1.3 PowerEdge C4140-K-V100-16GB SXM2 Single Node

![PowerEdge C4140: Configuration K (V10016GB-SXM2): CNN Performance (images/second) Single Node (1, 2, 3 and 4 GPUs)](image2)

Figure 17: PowerEdge C4140-V100-16GB-SXM2 in single-node
7.1.4 PowerEdge C4140-K V100-32GB SXM2 Single Node

![Figure 18: PowerEdge C4140-V100-32GB-SXM2 in single-node](chart.png)
Deep Learning Performance: Scale-up vs Scale-out

7.1.5 PowerEdge C4140-M- V100-16GB SXM2 Single Node

![Graph showing training performance with C4140-M-V100-16GB-SXM2](image)

**Figure 19. PowerEdge C4140-M-V100-16GB-SXM2 in single-node**

7.1.6

7.1.7 PowerEdge C4140- V100-SXM2 Configuration K versus Configuration M - Single Node

The plot below is a comparison showing performance difference between Config-K and Config-M, although it’s not a like-like comparison because of CPU difference. Config-K has Intel Xeon 4116 @ 2.1GHz 12core processor Vs Config-M which has Intel Xeon 6148 @2.4GHz 20 cores. The number of CPU cores does matter and in one of the later plots, we will show the difference in performance using different processors with same PCIe topology.
As shown in Figure 21 below, it shows that the number of CPU cores does play a role in terms of throughput. And the biggest difference is when running AlexNet.

7.1.8 What role does CPU play in Deep learning?
The CPU plays a major role in the initial phase called data preprocessing. The steps below show an instruction pipeline, with the following 4 instructions happening in parallel:

a. Train on batch n (on GPUs)

b. Copy batch n+1 to GPU memory

c. Transform batch n+2 (on CPU)

d. Load batch n+3 from disk (on CPU)

The loop for the data processing when training is:

a. Load mini-batch

b. Preprocess mini-batch

c. Train on mini-batch
As you notice in Figure 21, there is a slight performance difference for most of the neural models when using Intel Xeon 6148 except for AlexNet where it shows almost doubling in performance.

There are quite a few in-depth articles in showing the architecture for AlexNet and at some later point we will try to explain why AlexNet behaves differently based on the number of CPU cores and frequency.
7.1.9 Conclusion

7.1.9.1 Single Node: 1GPU

Figure 22: PowerEdge C4140-B V100-16GB PCIe Vs C4140-K V100 SXM2 – 1GPU
### 7.1.9.2 Single Node: 4GPU

#### Figure 23: PowerEdge C4140-B P100-16GB PCIe vs C4140-K V100-SXM2: 4GPU

- As shown in the plots above in Figure 22 and Figure 23 there is not much difference in throughput (images/sec) when comparing PowerEdge C4140-Configuration B with V100-16GB PCIe GPU and Configuration K with V100-16GB SXM2 GPU. The reason is in both configurations GPUs are in peer-peer mode behind PCIe Switch.
- C4140-M shows higher performance compared to C4140-K when using either Intel Xeon CPU with 12 cores or Intel Xeon CPY with 20 cores.
7.1.10 Non-Dell EMC server: 8x V100-16GB-SXM2 – Single Node

Figure 24: Non-Dell EMC 8x V100-16GB-SXM2 performance
Deep Learning Performance: Scale-up vs Scale-out

7.2 Throughput images/s – Multi Node

7.2.1 PowerEdge C4130-P100 16GB PCIe- Multi Node
PowerEdge C4130 each with 4 P100-PCle GPUs were configured in multi-node using InfiniBand RDMA to run the TensorFlow in distributed mode.

![Distributed Horovod Training with C4130-P100-16GB-PCle- CNN Performance (images/second)](image)

**Figure 25**: Training with PowerEdge C4130-P100-16GB-PCle in multi-node

PowerEdge C4130 server scales very well within a node with 97% efficiency and 92% across the nodes. The ideal performance is computed by multiplying the single-GPU throughput by the number of GPUs in the system. See Figure 26.
Figure 26: Scaling Efficiency of C4130-P100-16GB-PCle across multi GPUs and multi nodes
PowerEdge C4140-K-V100-16GB and V100-32GB: SXM2 Multi Node

PowerEdge C4140-V100-16GB-SXM2 and PowerEdge C4140-V100-32GB-SXM2 with 4 GPUs each were configured in multi-node to run the TensorFlow in distributed mode, extract the throughput performance, and determine its scaling efficiency. The GPUs scale very well within a node to 97% and 90% across the nodes. The ideal performance is computed by multiplying the single-GPU throughput by the number of GPUs in the system. See Figure 28
Figure 28: Scaling Efficiency of PowerEdge C4140-V100-16GB-SXM2 and PowerEdge C4140-V100-32GB-SXM2 across multi GPUs and multi nodes
7.2.3 PowerEdge C4140-M-V100-16GB-SXM2 Multi Node

![Distributed Training with C4140-M-V100-16GB-SXM2- CNN Performance (images/second) Workload: 100 training steps, Imagenet dataset, 128 mini-batch size per GPU](image)

Figure 29. Training with PowerEdge C4140-M-V100-16GB-SXM2 in multi-node
DEEP LEARNING PERFORMANCE: SCALE-UP VS SCALE-OUT

7.2.4 PowerEdge C4140-K Multi Node Training vs Non-Dell EMC 8x V100-16GB-SXM2

The Non-Dell EMC 8x V100-16GB- SXM2 system was tested on Nimbix cloud.

Figure 31 shows its throughput performance of 8X SXM2 and shows the comparison versus PowerEdge C4140-K-V100 in distributed mode (8 GPUs).
Table 5: 8x GPU Comparison between PowerEdge C4140-K multi-node and 8X SXM2

<table>
<thead>
<tr>
<th>Model</th>
<th>SN_8X V100_16GB- SXM2</th>
<th>MN- PowerEdge C4140-K-V100-16&amp;32GB-SXM2 (16Gb &amp;32GB)-IntelXeon4116</th>
<th>% Diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inception-v4</td>
<td>1606</td>
<td>1625</td>
<td>-1.21%</td>
</tr>
<tr>
<td>VGG-19</td>
<td>2449</td>
<td>2406</td>
<td>1.78%</td>
</tr>
<tr>
<td>VGG-16</td>
<td>2762</td>
<td>2820</td>
<td>-2.03%</td>
</tr>
<tr>
<td>Inception-v3</td>
<td>3077</td>
<td>2845</td>
<td>8.16%</td>
</tr>
<tr>
<td>ResNet-50</td>
<td>4852</td>
<td>4500</td>
<td>7.81%</td>
</tr>
<tr>
<td>GoogLeNet</td>
<td>7894</td>
<td>8754</td>
<td>-9.82%</td>
</tr>
<tr>
<td>AlexNet</td>
<td>16977</td>
<td>12145</td>
<td>39.79%</td>
</tr>
</tbody>
</table>

As seen from the table above, using PowerEdge C4140 with SXM2 shows pretty good performance across various pre-trained neural models. The most common ones i.e. ResNet-50 and Inception-v3 show performance within 8% of 8X SXM2. The only exception is AlexNet where it shows quite a bit of difference between 8X SXM2 and PowerEdge C4140.

The good performance shown by PowerEdge C4140 in multi node mode, comparable to a single node server 8x V100-16GB, was reached after the right software stack configuration with the...
distributed framework Horovod over IB/GPUDirect-RDMA, see below Figure 32 the scaling efficiency reached by PowerEdge C4140:

Figure 32: The Performance with Distributed Horovod TensorFlow, connected by Mellanox ConnectX-5 network adapter with 100Gbit/s over IPoIB, and GPUDirect RDMA
Deep Learning Performance: Scale-up vs Scale-out

7.2.5 PowerEdge C4140-M Multi Node Training vs Non-Dell EMC 8x V100-16GB-SXM2

In the **Figure 33** above we can appreciate the throughput improvement when using a sever with a higher capacity CPU; as seen in the table below, almost all the models trained with C4140-M-V100-16GB-SXM2 - CPU IntelXeon6148 (8 GPUs) – multi-node performed better than SN-8xV100. The exception was AlexNet which still performed under SN_8xV100; however, it improved its throughput significantly compared when trained with the server with C4140-K-V100-16GB-SXM2 - IntelXeon4116. See the summary in the below table

<table>
<thead>
<tr>
<th>Model</th>
<th>SN_8X V100_16GB- SXM2</th>
<th>MN- PowerEdge C4140-M-V100-SXM2 16GB</th>
<th>% Diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inception-v4</td>
<td>1606</td>
<td>1993</td>
<td>19%</td>
</tr>
<tr>
<td>VGG-19</td>
<td>2449</td>
<td>3205</td>
<td>24%</td>
</tr>
<tr>
<td>VGG-16</td>
<td>2762</td>
<td>3734</td>
<td>26%</td>
</tr>
<tr>
<td>Inception-v3</td>
<td>3077</td>
<td>3685</td>
<td>16%</td>
</tr>
<tr>
<td>ResNet-50</td>
<td>4852</td>
<td>5904</td>
<td>18%</td>
</tr>
<tr>
<td>GoogLeNet</td>
<td>7894</td>
<td>10801</td>
<td>27%</td>
</tr>
<tr>
<td>AlexNet</td>
<td>16977</td>
<td>14969</td>
<td>-13%</td>
</tr>
</tbody>
</table>

Table 6: Table 5: 8x GPU Comparison between PowerEdge C4140-M multi-node and 8X SXM2
7.2.6 PowerEdge C4140 Multi Node Training with Different CPU Models vs 8x V100-16GB-SXM2

In the results shown in the Figure 31 and Figure 33 we configured the multi-node system with servers PowerEdge C4140-V100-SXM2- Configuration-K Intel Xeon4116 CPU and Configuration-M Intel Xeon6148 CPU respectively, versus single-node training non-Dell EMC 8xV100-16GB-SXM2.

To show the impact of the CPU in the training of deep learning workloads, we run additional tests configuring the multi-node system with servers PowerEdge C4140-V100-SXM2 Configuration-M and Intel Xeon6148 CPU. In the Figure 34 we see how advance CPU models boost even more the gpu performance, since most of the data loading, data preprocessing, and batch transformation tasks occur at the CPU level, whereas the training tasks occur at the gpu level.

Figure 34. Multi-node training PowerEdge C4140-V100-SXM2- Configuration-K with IntelXeon4116 cpu, Multi-node training PowerEdge C4140-V100-SXM2 Configuration-M with IntelXeon6148 cpu, versus single-node training non Dell 8xV100-16GB-SXM2
7.3 Results Showing Training Time Vs Accuracy

These tests were run with 90 epochs to determine training time to achieve top-1% and top-5% accuracy.

Figure 35 shows the results for the server 8X SXM2, POWEREDGE C4140-V100 in single and multi-node mode, C4130-P100 in single and multi-node mode, and R740-P40.

Results Highlights

- The fastest training time was achieved by the system 8X SXM2 with 93% of accuracy convergence in 6.6 hours.
- PowerEdge C4140 – Configuration K with SXM2 in multi-node configuration achieved 95% of accuracy convergence in 7.2 hours.
- R740-P40 with 48.8hrs and 93% of accuracy convergence.

Figure 35: Longest tests to extract accuracy convergence and training time
Figure 36: Relative speed performance based on training time

After training the PowerEdge C4140 – Configuration M with SXM2 in multi-node configuration, we saw it reached the fastest training in 5.3 hours, overpassing the Non-Dell EMC SN_8x-V100-16GB-SXM2 which completed the training time in 6.6 hours. See Figure 36.

7.3.1 Elapsed Training Time for Several Models

Another aspect we wanted to explore was the accuracy convergence capacity for other models, so we selected models with different depth network topology (vg199, ResNet50, and Inception-v4) and ran the long tests on PowerEdge C4140 in multi-node configuration and non-Dell EMC 8x – V100 SXM2. The results are show in Figure 37 below.
Figure 37: Training long tests to extract accuracy convergence and training time with 8X SXM2 and different models.

In the figure above, we observe that the models ResNet50 and Inception-v4 reached between 92%-96% of accuracy convergence in 90 epochs; however, ResNet50 with different batch sizes.
converged faster than Inception-v4. On the other hand, the model VGG-19 didn’t produce acceptable accuracy suggesting it requires over 90 epochs to converge.

*Figure 38* below show comparable results for PowerEdge C4140-K (multi-node) – V100 SXM2
### Distributed C4140-V100-32&16GB-SXM2 vs SN 8x V100-16GB-SXM2

<table>
<thead>
<tr>
<th>Batch Size</th>
<th>C4140</th>
<th>8x V100</th>
</tr>
</thead>
<tbody>
<tr>
<td>256</td>
<td>92% Acc</td>
<td>97% Acc</td>
</tr>
<tr>
<td>128</td>
<td>93% Acc</td>
<td>95% Acc</td>
</tr>
<tr>
<td>64</td>
<td>94% Acc</td>
<td>89% Acc</td>
</tr>
<tr>
<td>32</td>
<td>95% Acc</td>
<td>72% Acc</td>
</tr>
</tbody>
</table>

**Training Time to Reach Accuracy Convergence 72%-97%**

Workload: 8GPUs, Resnet50, 90 Epochs, Imagenet. Shorter training time is better

To show the impact of the CPU in the training of deep learning workloads to reach the accuracy convergence, we run additional tests configuring the multi-node system with servers PowerEdge C4140-V100-SXM2 Configuration-M and IntelXeon6148 CPU. In the **Figure 40** we see the multi-node system C4140-V100-SXM2 Configuration-M and IntelXeon6148 CPU performs **1.3X** faster than SN-8xV100 for the model resnet50 trained in several batch sizes. Again, it shows the relationship between the CPU model and the Deep Learning performance, where most of the data loading, data preprocessing, and batch transformation tasks occur at the CPU level, whereas the training tasks occur at the GPU level.
In the Figure 40 we can see how the system C4140-V100-SXM2 Configuration-M outperforms in terms of training time in different batch sizes compared the other systems.

7.4 Other Explored Aspects

This section shows the results of aspects explored during this project such as the hyper parameter tuning, learning rate effect on single-node and multi-node mode, and critical kernels executed in the TensorFlow benchmarks. These aspects could be subject of deeper study for future projects.
7.4.1  Hyper-parameters tuning

The section below are the commands with the hyper-parameter tuning used to maximize the throughput performance in single and distributed mode server implementations.

*Figure 41* shows the high impact of the hyper-parameter tuning in the throughput performance:

**Single Node – TensorFlow:**

```
#python3 tf_cnn_benchmarks.py --variable_update=replicated --
data_dir=/data/imagenet_tfrecord/train --data_name=imagenet --model=ResNet50 --batch_size=128 --device=gpu --num_gpus=4 --num_epochs=90 --print_training_accuracy=true --summary_verbosity=0 --momentum=0.9 --piecewise_learning_rate_schedule='0.4;10;0.04;60;0.004' --weight_decay=0.0001 --optimizer=momentum --use_fp16=True --local_parameter_device=gpu --all_reduce_spec=nccl --display_every=1000
```

**Distributed Horovod – TensorFlow:**

```
#mpirun -np 8 -H 192.168.11.1:4,192.168.11.2:4 -x NCCL_IB_DISABLE=0 -x NCCL_IB_CUDA_SUPPORT=1 -x NCCL_SOCKET_IFNAME=ib0 -x NCCL_DEBUG=INFO --bind-to none --map-by slot --mca plm_rsh_args "-p 50000" python tf_cnn_benchmarks.py --variable_update=horovod --
data_dir=/data/imagenet_tfrecord/train --data_name=imagenet --model=ResNet50 --batch_size=128 --num_epochs=90 --display_every=1000 --device=gpu --print_training_accuracy=true --summary_verbosity=0 --momentum=0.9 --piecewise_learning_rate_schedule='0.4;10;0.04;60;0.004' --weight_decay=0.0001 --optimizer=momentum --use_fp16=True --local_parameter_device=gpu --horovod_device=gpu --datasets_num_private_threads=4
```
7.4.2 Learning Rate Effect in Distributed Mode

In this experiment, we used the learning rate schedule as follows: the initial learning rate was set up to 0.4 for the first 10 epochs, after that the learning rate was decreased to 0.04 until the model reached 60 epochs of training, finally it was decreased to 0.004 until the end of the training with 90 epochs.

*Figure 42 & Figure 43* we show how learning rate has a different effect in single node versus multi node. In multi node mode the learning rate update is not reflected immediately and there is a delay until the change is reflected in every processor.
Deep Learning Performance: Scale-up vs Scale-out

Figure 42: Training with PowerEdge C4140-V100-16&32GB-SXM2 (4 GPUs) – single-node

Figure 43: Training with PowerEdge C4140-V100-16&32GB-SXM2 - Multi Node - 8 GPUs

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7.4.3 Communication and Neural Networks Primitives

We wanted to explore the critical kernels executed in one GPU when running the TensorFlow benchmarks, so we used the Nvidia profiling tool Nvprof to analyze one TensorFlow benchmark trained with C4130-P100-PCIe-16GB in multi-node.

*Figure 44* shows the critical kernels executed, we found that the communication primitives all reduce where called 38.4% of the time, it may suggest that the GPU may spend too much time exchanging and communicating rather than computing, this is something that can be explored in depth for future projects.

![Performance Critical Kernels (%)](image)

*Figure 44: Critical kernels executed when training with C4130-P100-16GB-SXM2 (8 GPUs) – multi-node*

CUDA Toolkit offers several performance analysis tools to optimize the performance of CUDA or OpenACC applications. The Visual Profiler nvvp traces CUDA activities, profiles CUDA kernels, and correlates performance instrumentation with source code. The tool Nvprof collects performance events and metrics; CUDA memcheck detects memory accesses issues, incorrect GPU thread synchronization and other important aspects to optimize performance [5].
8 Conclusion and Future Work

- PowerEdge C4140 using Nvidia 4x NVLink architecture scales relatively well when using Uber Horovod distributed training library and Mellanox InfiniBand RDMA as the high-speed link between nodes.

- Table 5 shows that PowerEdge C4140 in multi-node configuration for most widely used model ResNet-50 is within 7.8% of single node Non-Dell EMC 8x-NVLink system. But with C4140-M in multi-node out performs single node 8x NVLink by at least 18% using ResNet-50. The only disclaimer is that C4140-M results are using the latest version of NCCL & TensorFlow containers.

- There is lot of performance improvement being added continuously either at the GPU level, library level or framework level. We are continuously looking at how we can improve our performance results by experimenting with different hyper parameters.

- Some of our future work in this area will be related to exploring the latest software optimizations being released by Nvidia and looking at fast.ai library where Jeremy Howard and researchers at fast.ai achieved training time of 3 hours on 8x V100 on ResNet-50.
9 Citation

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Author = {Alexander Sergeev and Mike Del Balso},
Title = {Horovod: fast and easy distributed deep learning in {TensorFlow}},
Year = {2018}
}

10 References


