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Use of Parallel and High Performance Computing in Power Systems Simulations and Its Challenges

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Outline

- Background
- Situation
- Motivation for improvements
- Experimental developments
- Future targets

Background

- Engineers have always strived for methods for speeding-up the simulation computation time
  - by writing efficient algorithms
  - or, often have compromised and lived with coarse grained analysis due to large computation times
- Multiple-core computers at Engineer's disposal
  - have added to frustration
  - simulation software haven't caught-up with it yet

Background

The first 20 years

- For the first two decades of the software all implementations considered only a single process PSCAD and a single process EMTDC. This is for all versions up until v4.4 in 2011
- Quad core computers were not in general use until 2008.

Frequency of communication is *very low*. Messages are exchanged only at the beginning and end of a run.

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Need for speed…

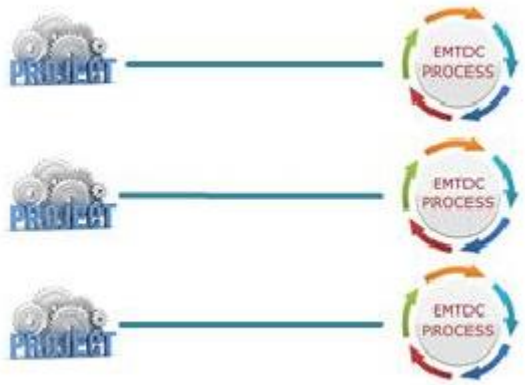
- PSCAD has been performing sequential computing for quite some time (since 1993).
- Lately, technology and developments have steered PSCAD to utilize **parallel and distributed computing** models of computation
  - Recent developments enable
    - Task Parallelism (MPMD)
    - Data Parallelism (SPMD)

  by using Message Passing over TCP/IP Inter-process communication (IPC) techniques

Changes

2011

- Utilizing existing implementations, changes were made to allow the application to accept multiple simulations to execute at the same time. All projects had to be independent and unique.
- Each had to be launched on an individual basis.

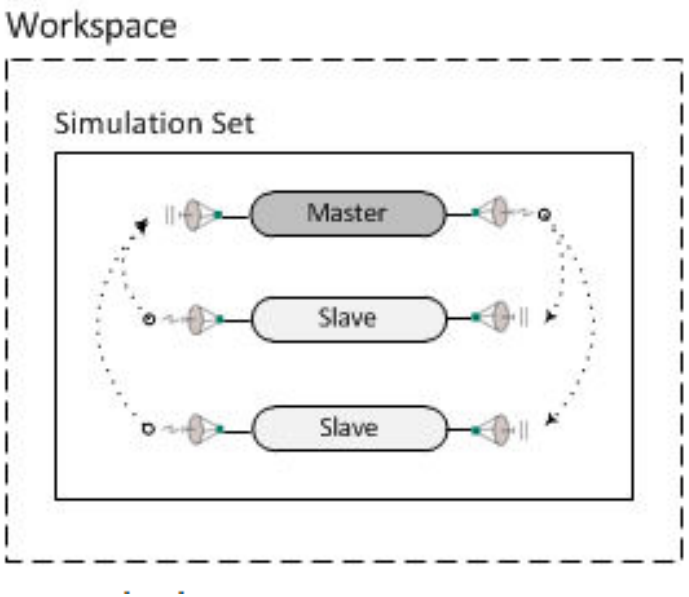


Frequency of communication is *very low*.
Messages are exchanged only at the beginning and end of a run.

Background

2012

- Data parallel approach allows for one root, or *master* project, to control multiple *slave* projects, where both *master* and *slaves* must be part of the same Simulation Set.



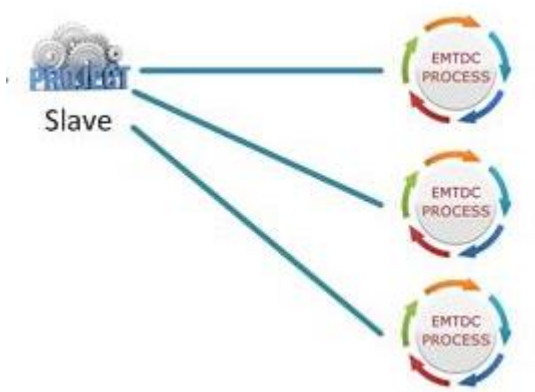
Frequency of communication is *very low*.
Messages are exchanged only at the beginning and end of a run.

Creates a parallel version of the multi-run interface

Background

2015 (Data Parallel Simulation)

- Significant refactoring of the run interface enabled the ability to execute coordinated sets of simulations.
- The launch system was expanded to enable a single project to spawn multiple copies of itself to execute under different conditions.



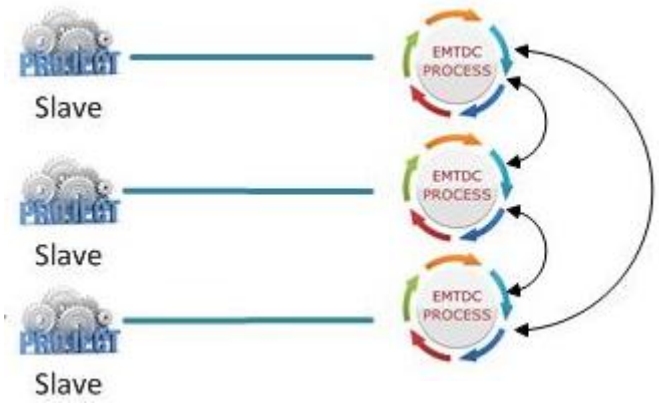
Frequency of communication is *very low*. Messages are exchanged only at the beginning and end of a run.

Creates a parallel version of the multi-run interface

Background

2015 (Task Parallel Simulation)

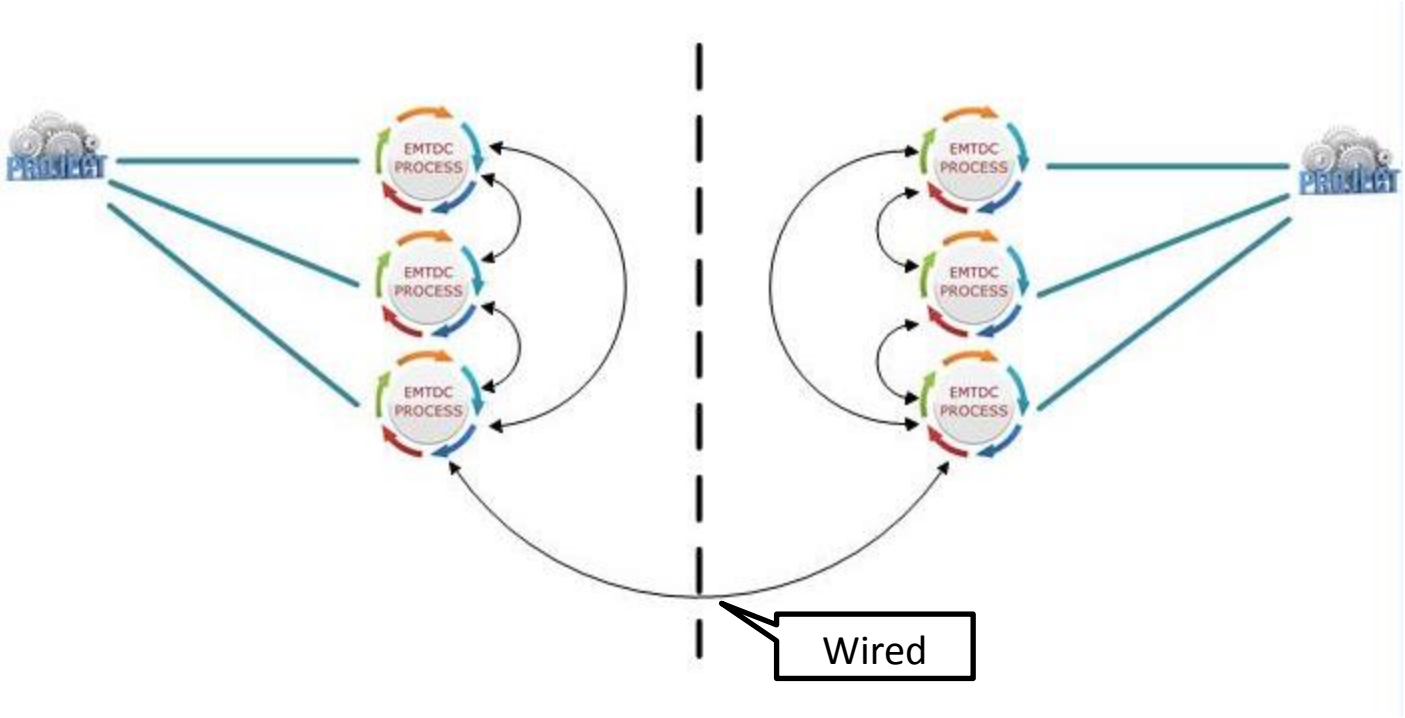
- A single electric network may be split so that each electric subsystem is represented by a separate project, and thereby runs using separate processes.
- Each process is linked together via a *Communication Interface* to form a cohesive simulation that is run from within a single workspace.



Frequency of communication is *high*.
Messages are exchanged every time step.

Co-Simulation

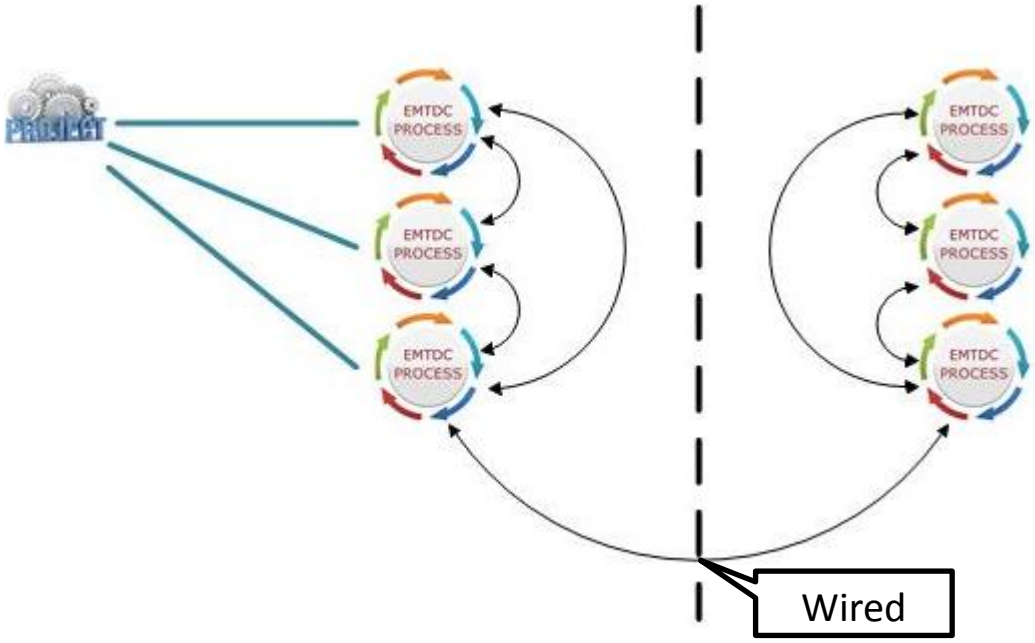
2015 (Coordinated Task Parallel Simulation)



Using the transmission line interface, multiple PSCADs can be tethered together to co-simulate a larger network on separate computing platforms.

Co-Simulation

2015 (Xoreax Grid Engine Deployment)



Using the transmission line interface, multiple PSCADs can be tethered together to co-simulate a larger network on separate computing platforms.

PSCAD v4.6

Parallel and Distributed computing software

- Task Parallel and Data Parallel approach
  - Utilizes all cores on Localhost
  - Extends it to utilizing LAN

Benefits

  - Performance is increased many fold
  - Task Parallel
    - Orders of magnitude improvements (large cases – Province wide power network)
    - Very large networks handled easily
  - Data Parallel
    - Parametric studies that took months can be done in days or hours
    - Fine grained studies could be performed in reasonable time

Situation

Need for speed…

- To run simulations with greater fidelity in the same time or less, we need
  - Parallel computing capabilities
  - Less interference from operating system actions
  - Many cores on a single CPU with high clock speed
    - Typical desktop has 4 or 6 cores per CPU with one or two slots
    - Blade computers provide many cores, with 2 to 4 slots. (Slower Clock)

- Task Parallel
  - High frequency of communication, not a high volume.
  - Communication backplane is **standard TCP/IP network**
    - Relatively high communication latency on across LAN.
    - Relatively low communication latency on local host, **still not so efficient**.

Experimental Methodology

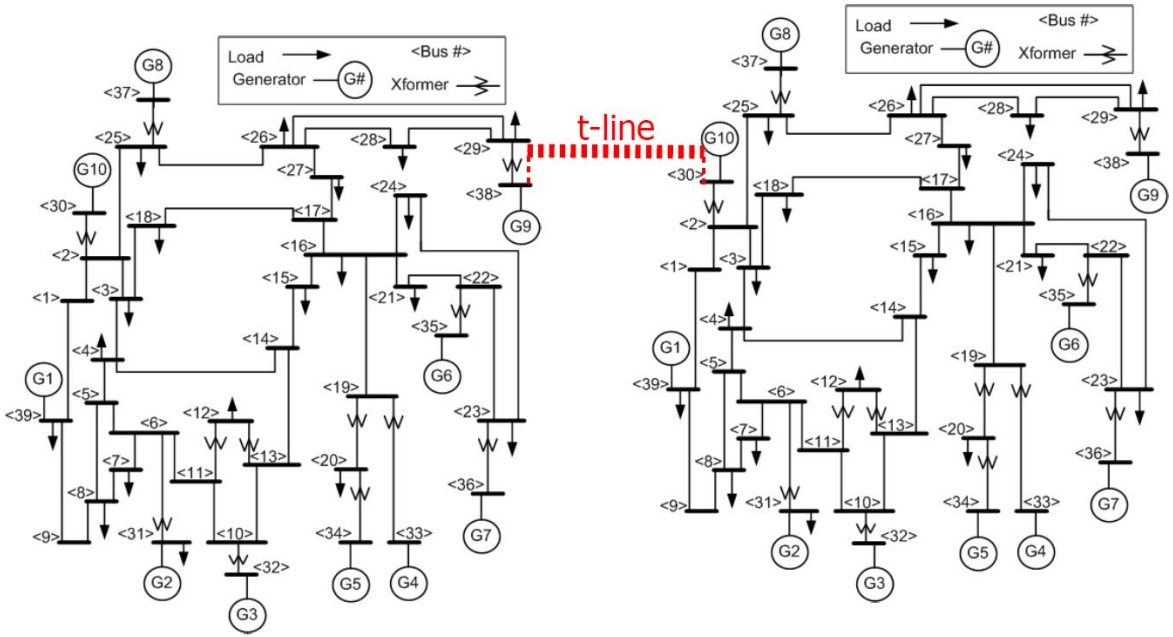
impact of communication and latency

- Several equal sized IEEE bus system kernels were connected using transmission-lines to create a large hypothetical bus system
  - for e.g. 273 bus system created by connecting 7 IEEE 39 bus system kernels
  - Experiments were performed with IEEE 14, 39, 78, 118 and 300 bus systems
    - largest hypothetical bus system being 300 X 7 = 2100 bus system

Experimental setup –

impact of communication and latency

IEEE 39 Bus



Experimental setup –

impact of communication and latency

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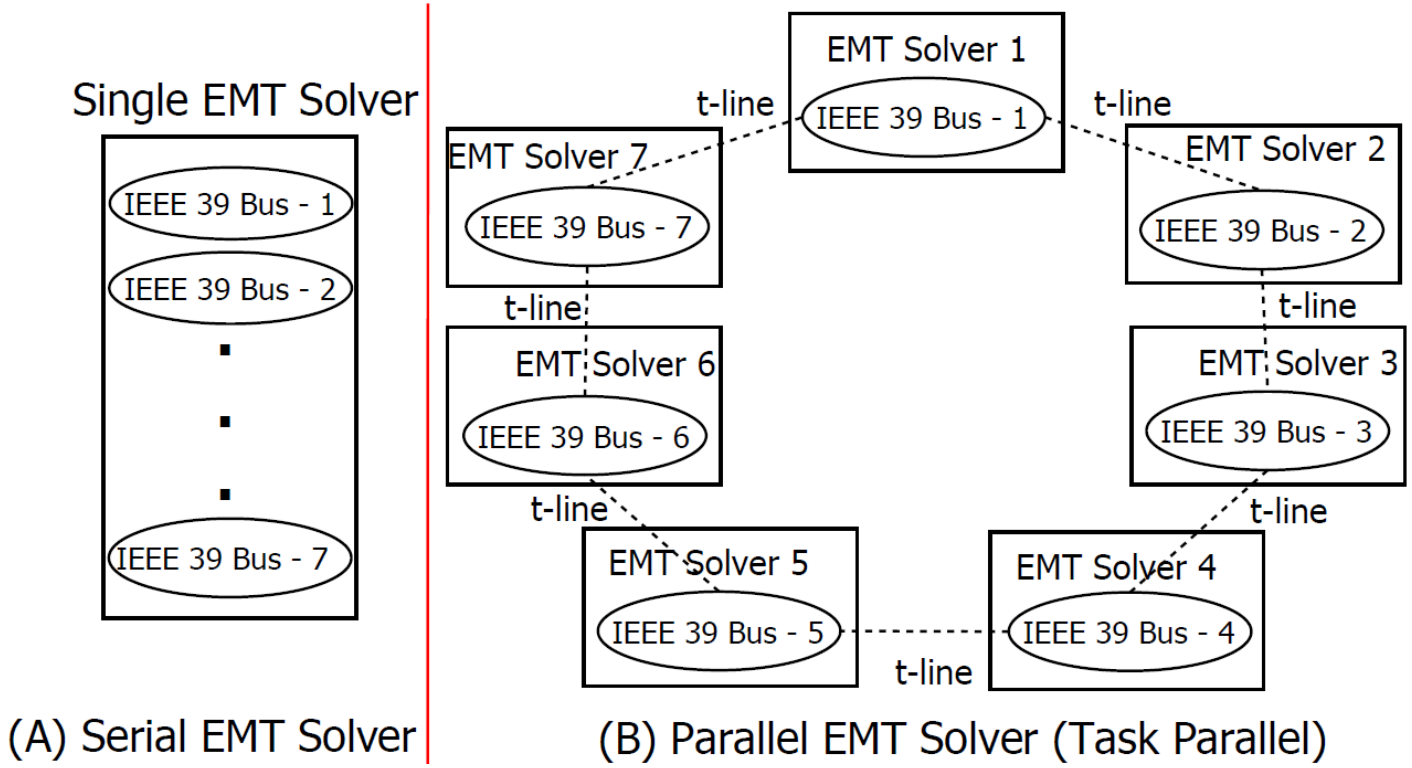
Contrived balanced system



Synthetic system designed to measure communication performance

Impact of communication and latency on Task Parallel

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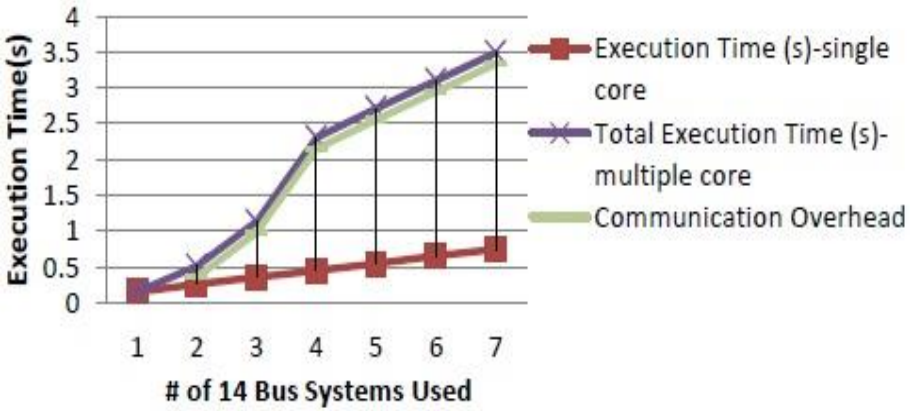
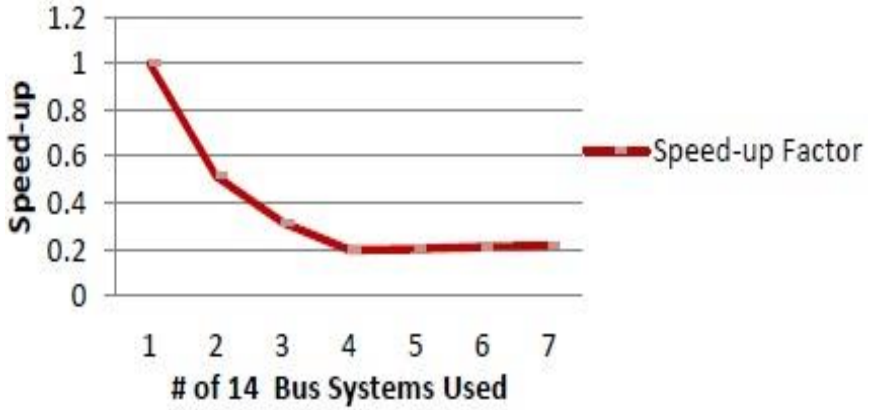
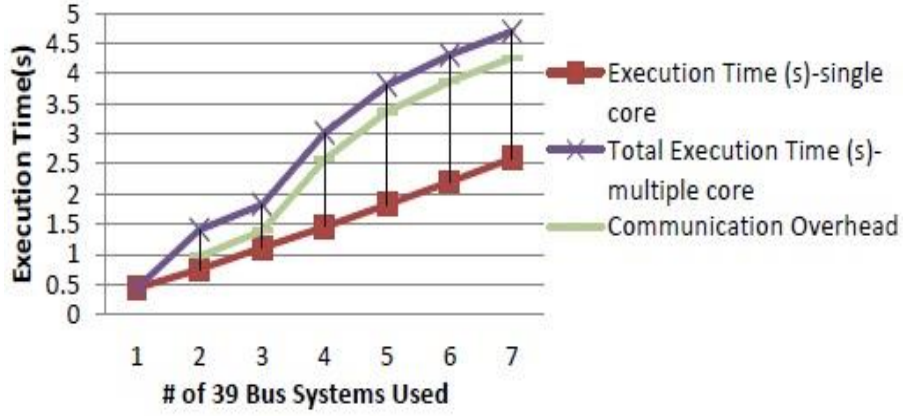
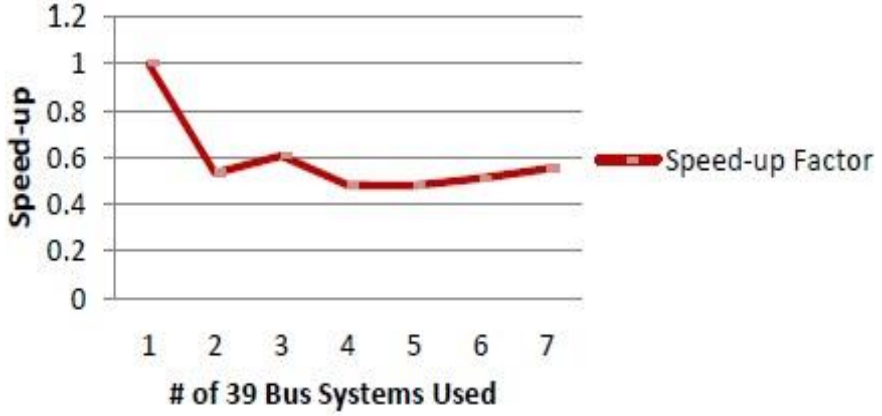
IEEE 14 Bus





IEEE 39 Bus





Impact of communication and latency on Task Parallel …

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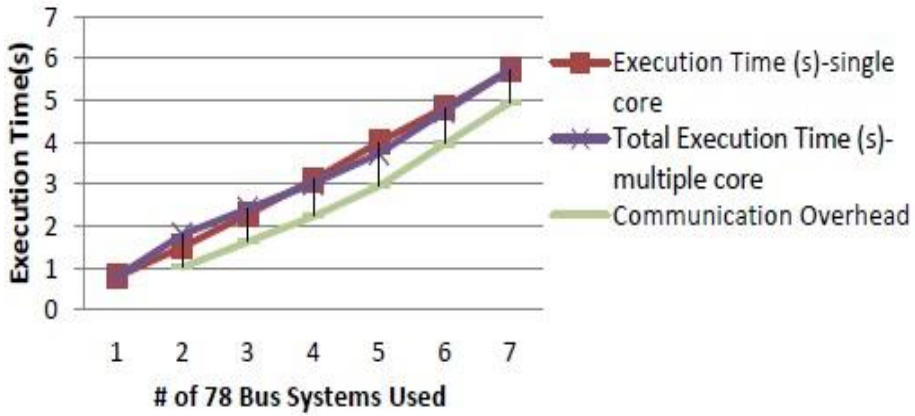
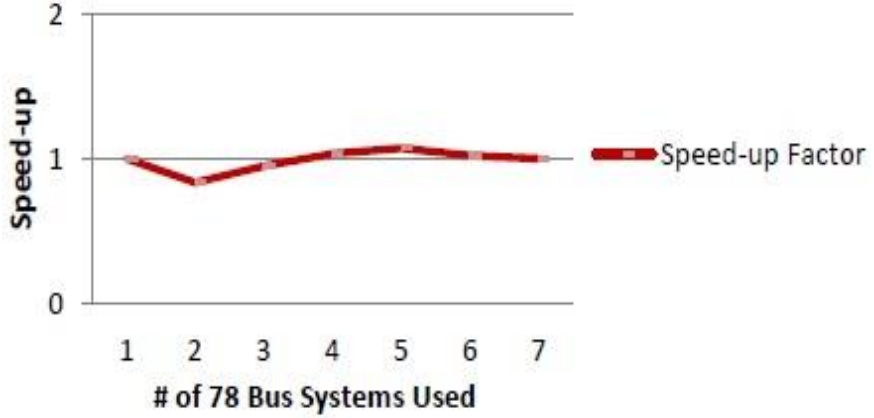
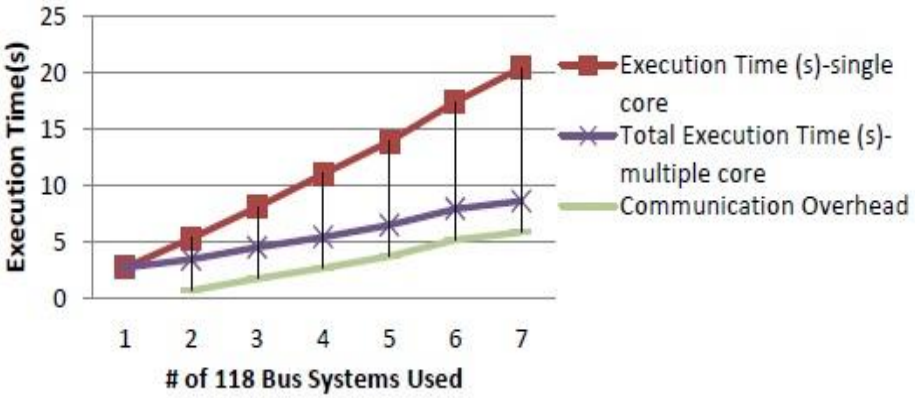
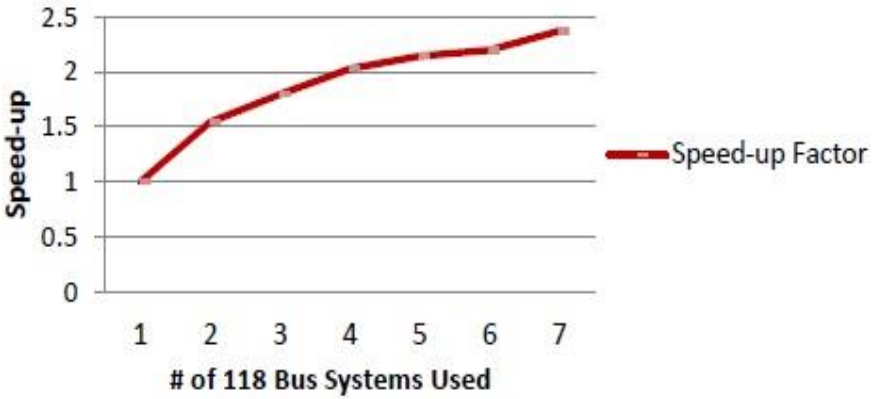
IEEE 78 Bus





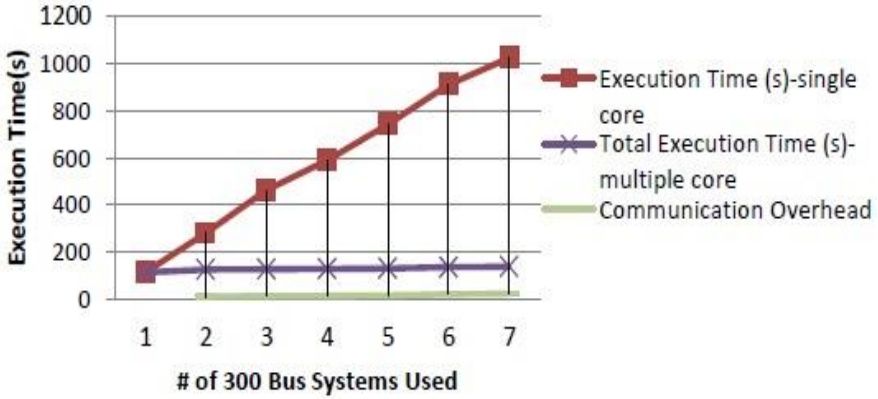
IEEE 118 Bus

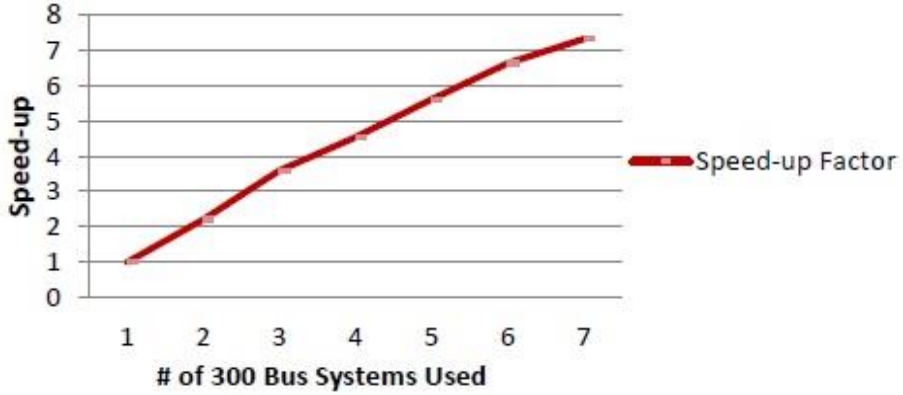




Impact of communication and latency on Task Parallel …

IEEE 300 Bus





Impact of Communication and Computation Grain on Task Parallel …

$$\left(\frac{T_{sol}}{X} + (T_{comm} \times Z)Y \right) \approx T_{total}$$

and

$$(X-1) \leq Y \leq \left(\frac{X(X-1)}{2} \right)$$

Where:

T_{sol} is computation time per sub-network

T_{comm} is communication time per message

X is number of decoupled sub-networks

Y is number of connections

Z is number of transmission lines

T_{total} is the total computation time of entire network

$\left(\frac{X(X-1)}{2} \right)$ is the maximum edges in a undirected graph

Motivation

For further improvements

- The key for performance gain is smaller computation grains
  - That is why we break larger cases into smaller cases
  - But granularity of the case is limited by the **communication speed**
    - If communication speeds are higher we can also speed-up smaller cases
- Clearly, communication becomes a bottleneck with smaller size of cases.
  - 78 Bus is a significant size
    - **Can this be reduced ?**

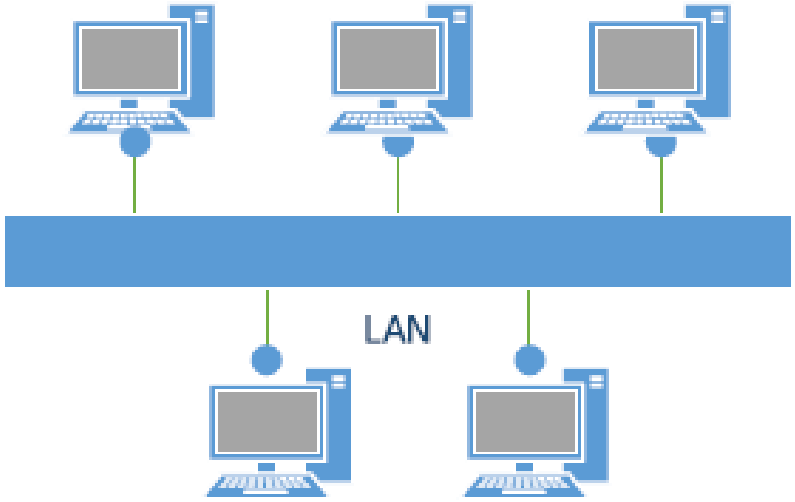
Motivation

For improvement

If we only have TCP/IP as a communication method, speed is heavily impacted by transport across nodes.

- Communication latencies are less within a node (20 us on TCP/IP) – **Can we reduce this ?**
- Communication latencies over multiple nodes are (230 us on TCP/IP) – **Can we reduce this ?**

We would like to avoid transport, but we *do not* have enough cores in a single compute node to fit all pieces of a simulation!



Motivation…

Multiple inter-connected multi-core

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Assumptions

- It is possible to achieve extremely fast communication speeds – *both local-host and inter-host*
- It is possible to break a large simulation into 100 smaller sub-systems
  - But typical desktops have only 12 or less cores
    - *Impossible to include all sub-systems*
  - We *need* multiple compute nodes connected to each other.

Will the combination of super-computing network hardware give us this capability?

High Performance Computing (HPC)

- The current design supports *Parallel Computing* through Task and Data Parallel approaches
  - Achieving performance figures never seen before in offline EMT tools.
  - But, we still use standard TCP/IP as communication backplane

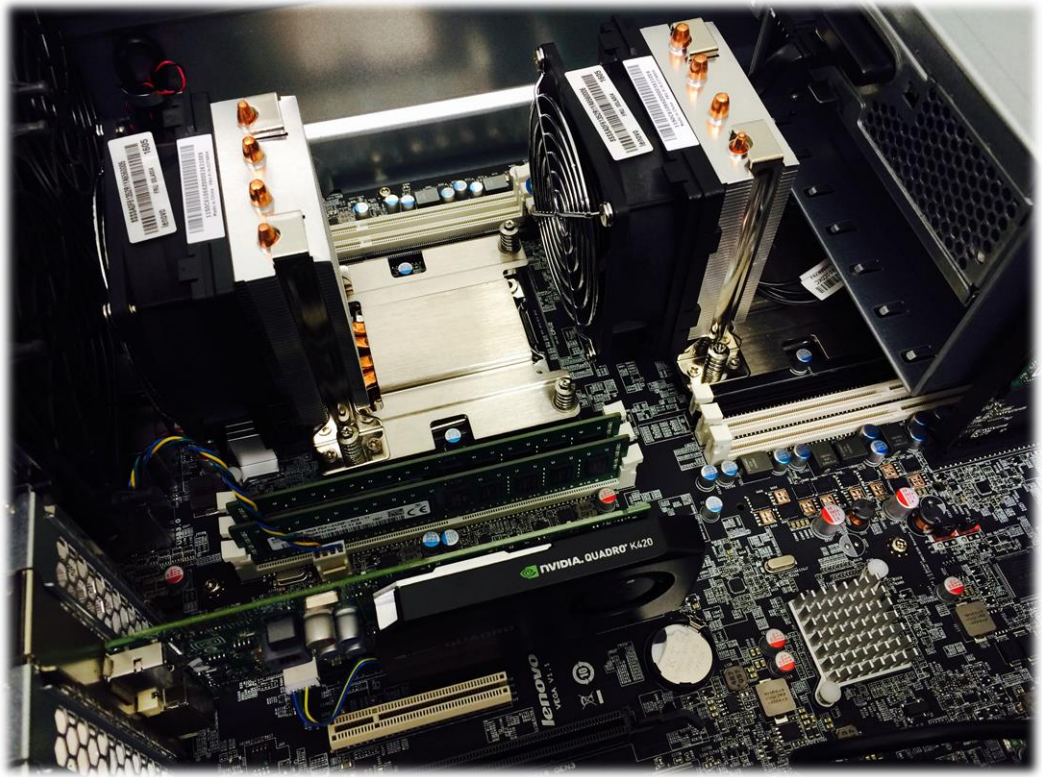
- Further, performance can be improved using HPC methods.
  - Communication using a *Shared Memory* software model.
  - Communication using *InfiniBand* ultra fast networking hardware. Fourteen Data Rate (FDR), 14.0625 Gbps
  - A hybrid solution using a combination of both.

On going experimental developments…

Experimental Test Rig

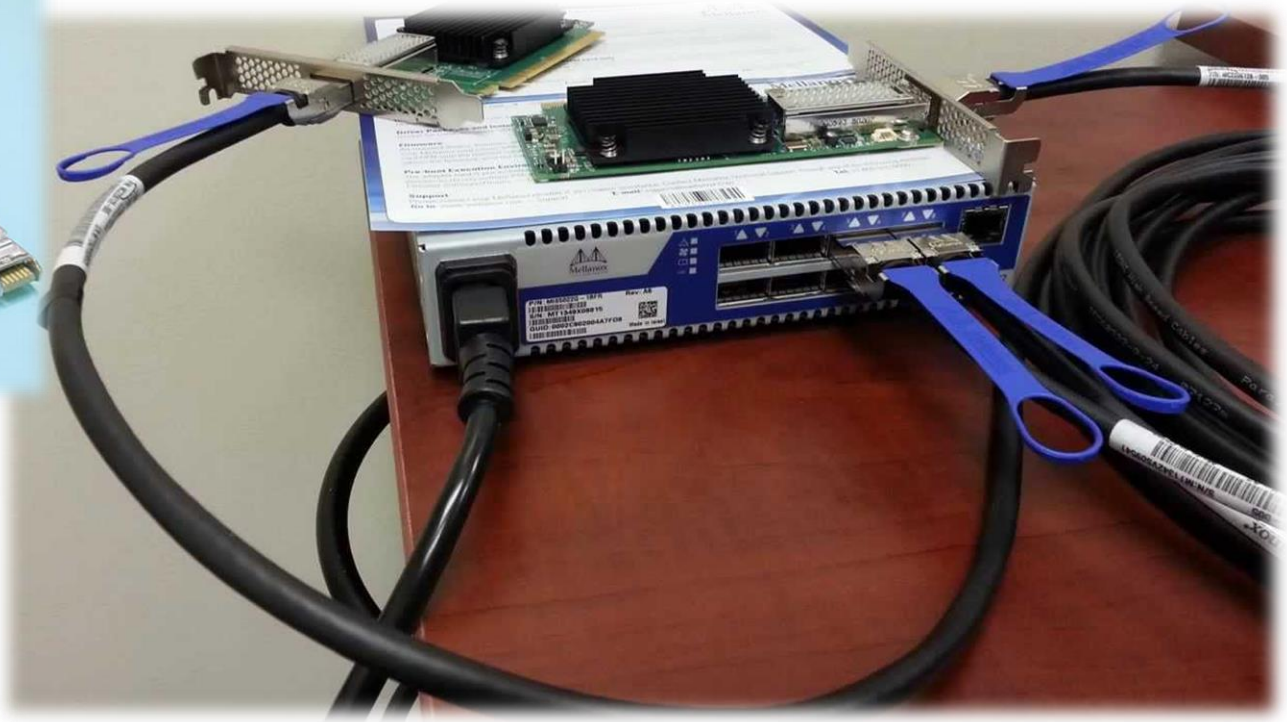
TITANUS (Quad-Slot) 64x Core

Experimental Test Rig



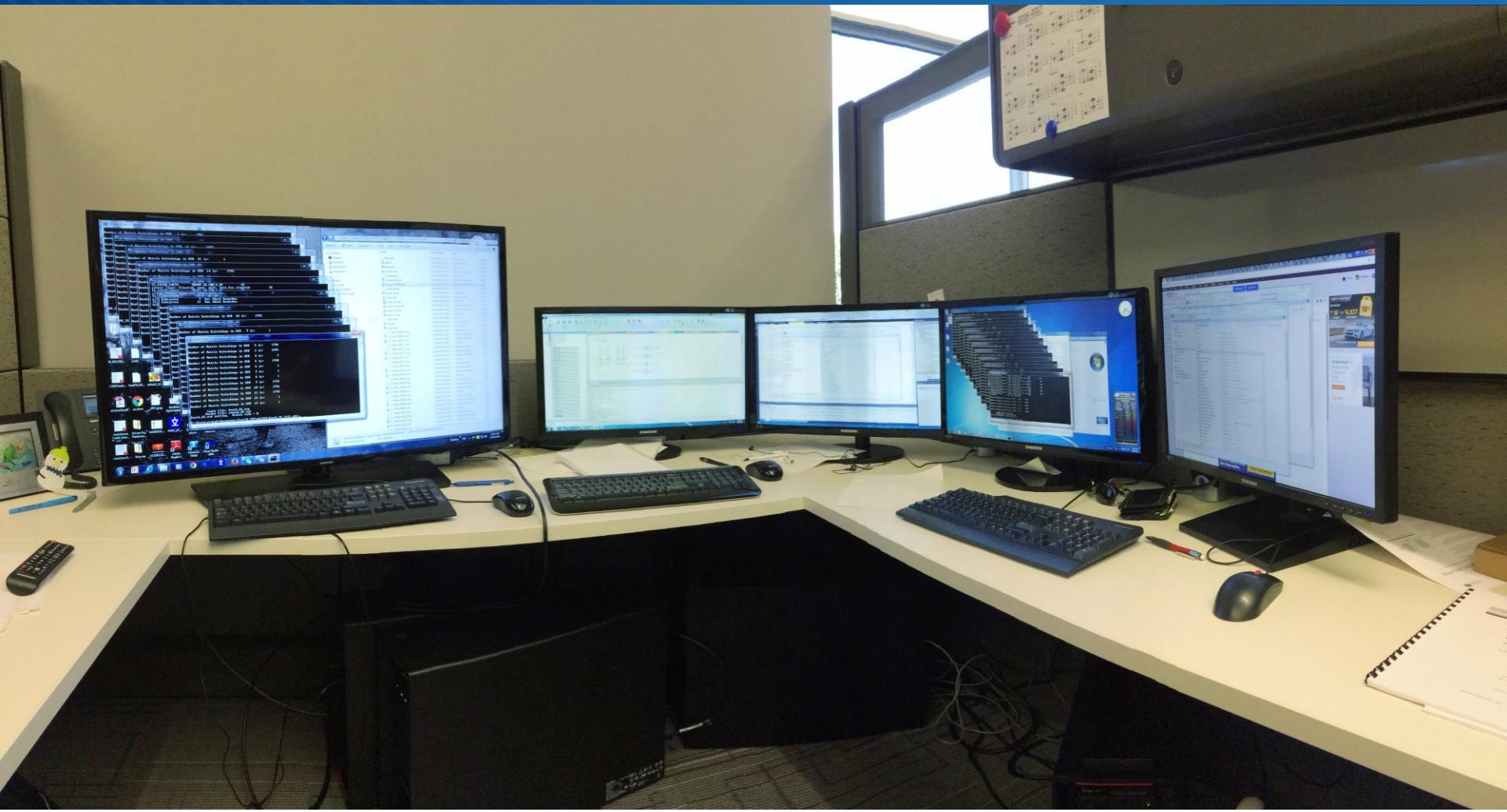
P900 Single Compute Node (Dual-Slots) 40x Core

Experimental Test Rig



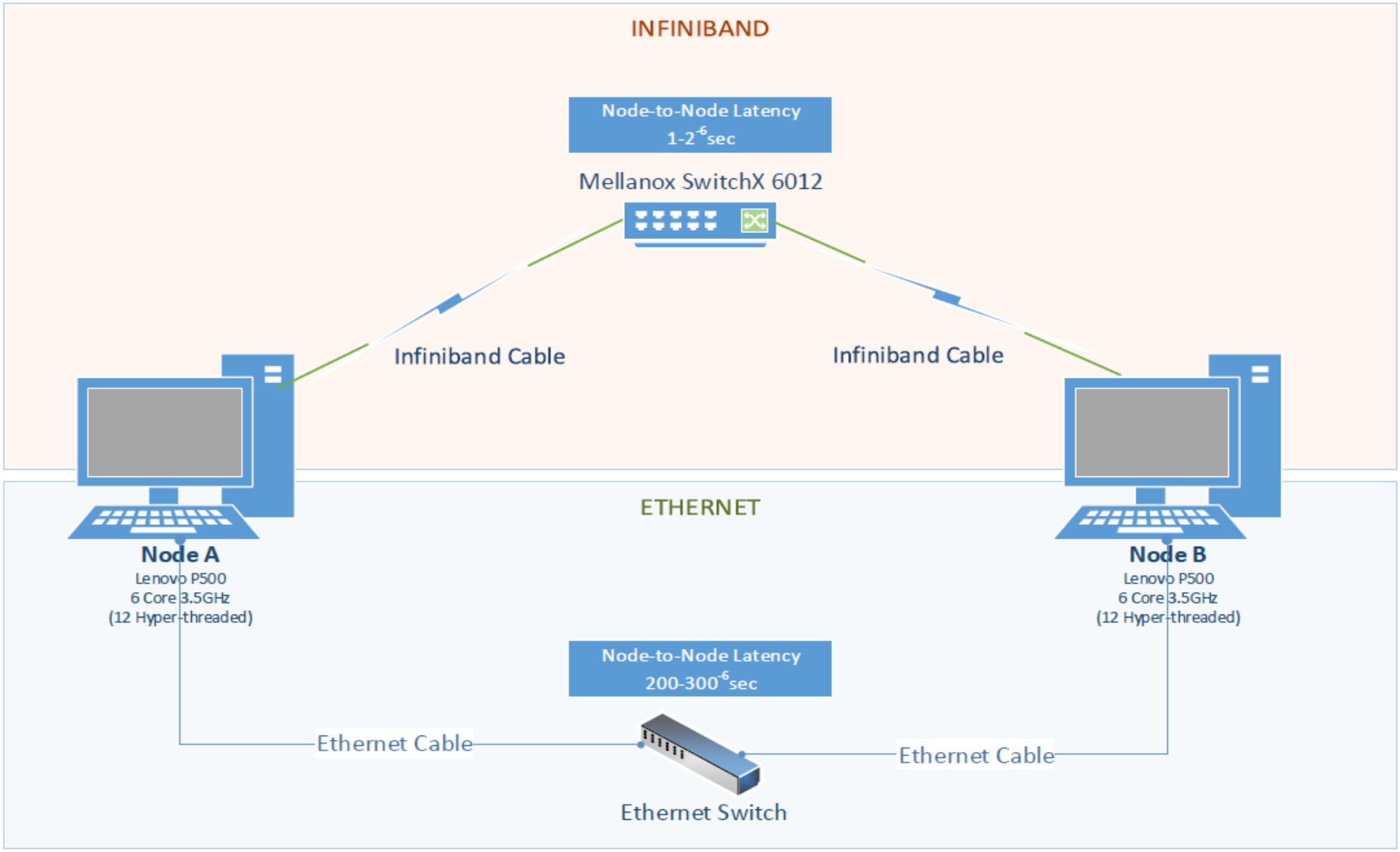
InfiniBand Switch/Cables and FDR Host Adaptors

Experimental Test Rig



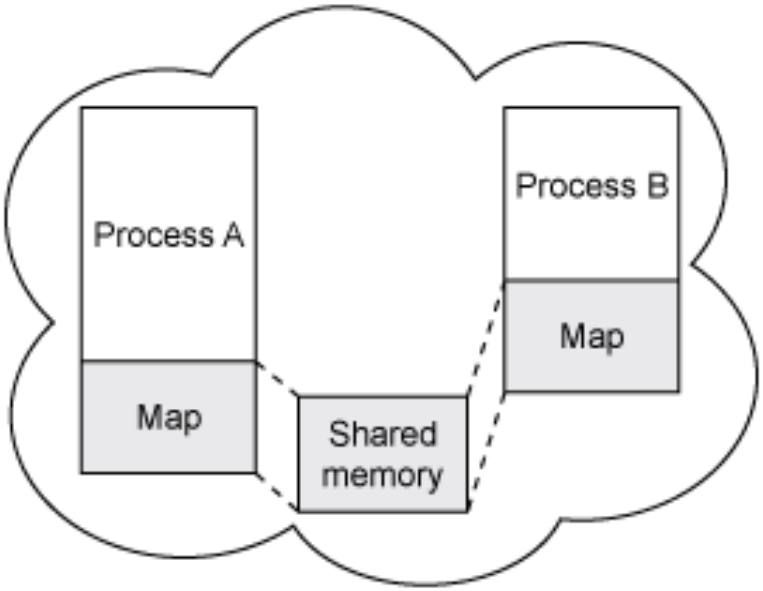
Experimental Test Rig

Experimental Test Rig



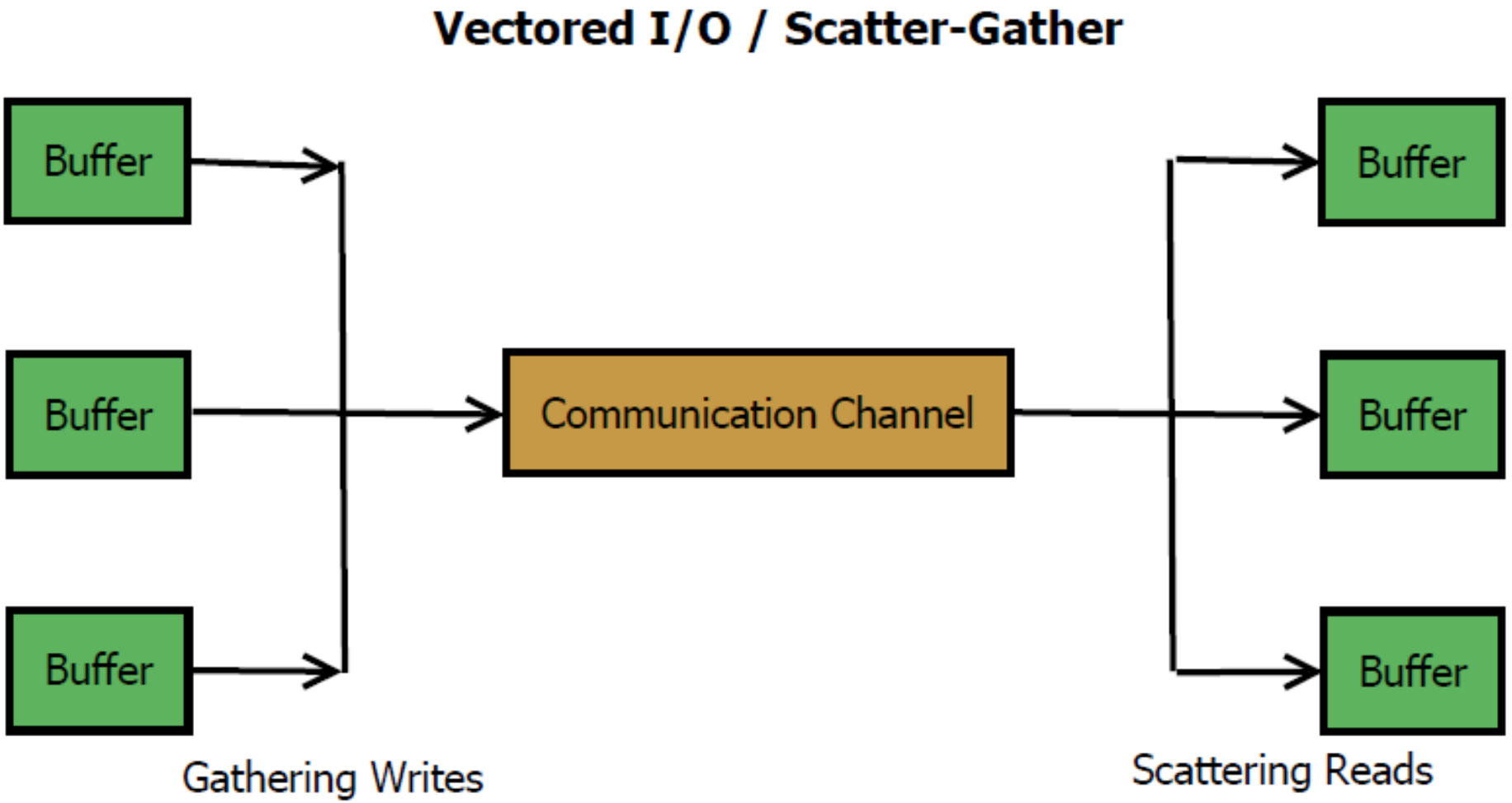
Shared Memory Model

- Multiple processes share memory blocks in the *local system*
  - Inter-process communication is fast due to low memory access latencies
  - Methods cannot communicate between nodes.
  - Processes can communicate using a lightweight trade mechanism.
  - Channels are multiplexed into and out of shared storage.

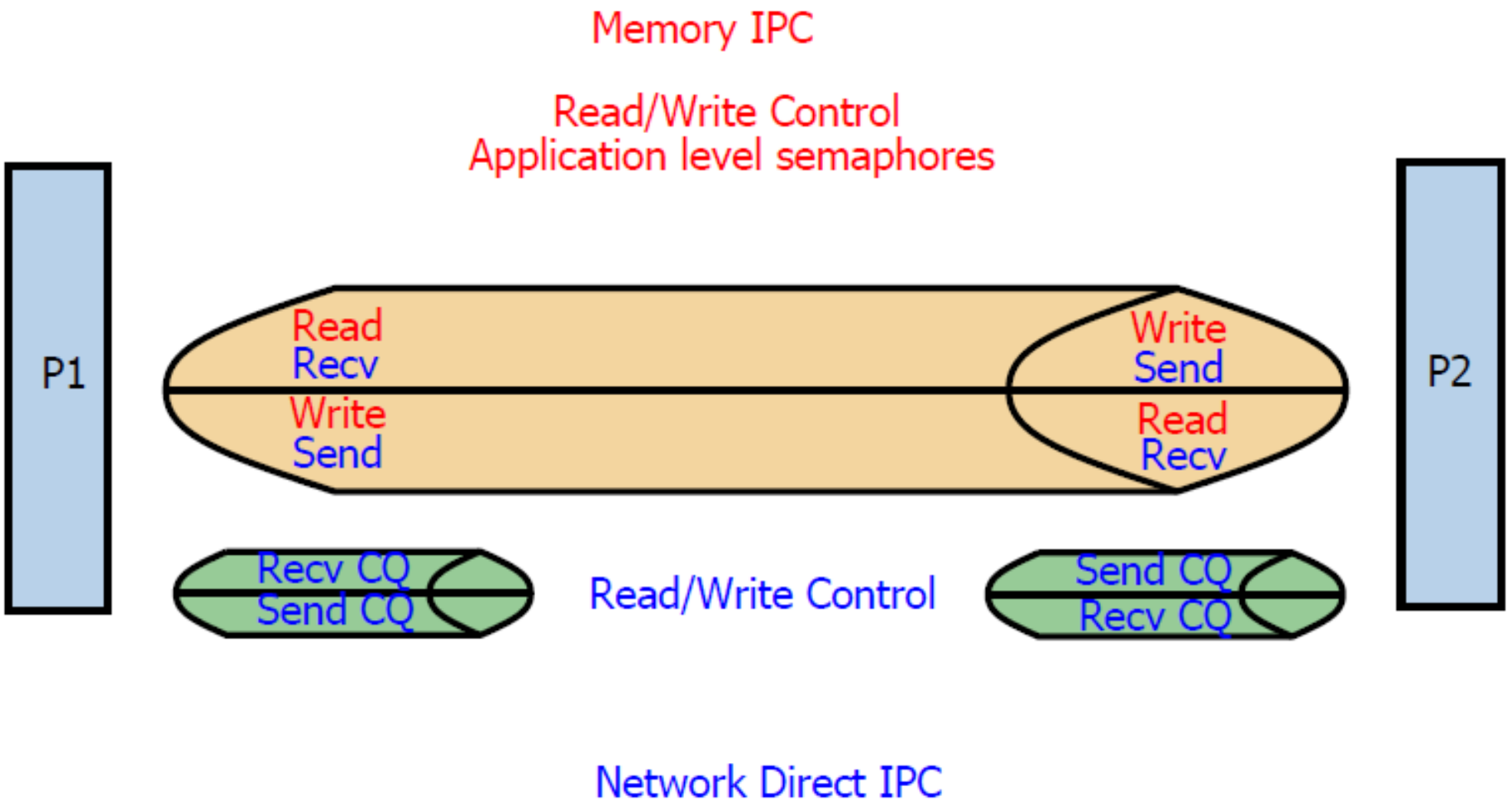


Communication latencies are in the range of 0.001 to 1us

Vectored I/O / Scatter-Gather



Communication IPC



Cross Node Communication

Remote Direct Memory Access

- **R**emote
  - Memory data transfers *between nodes in a network*
- **D**irect
  - Operating System Kernel by-passed in transfers
  - Transfer off-loaded onto Network Card processor.
- **M**emory
  - Transfers between user space application's virtual memory
  - Zero extra copying or buffering
- **A**ccess
  - send, receive, read, write, atomic operations

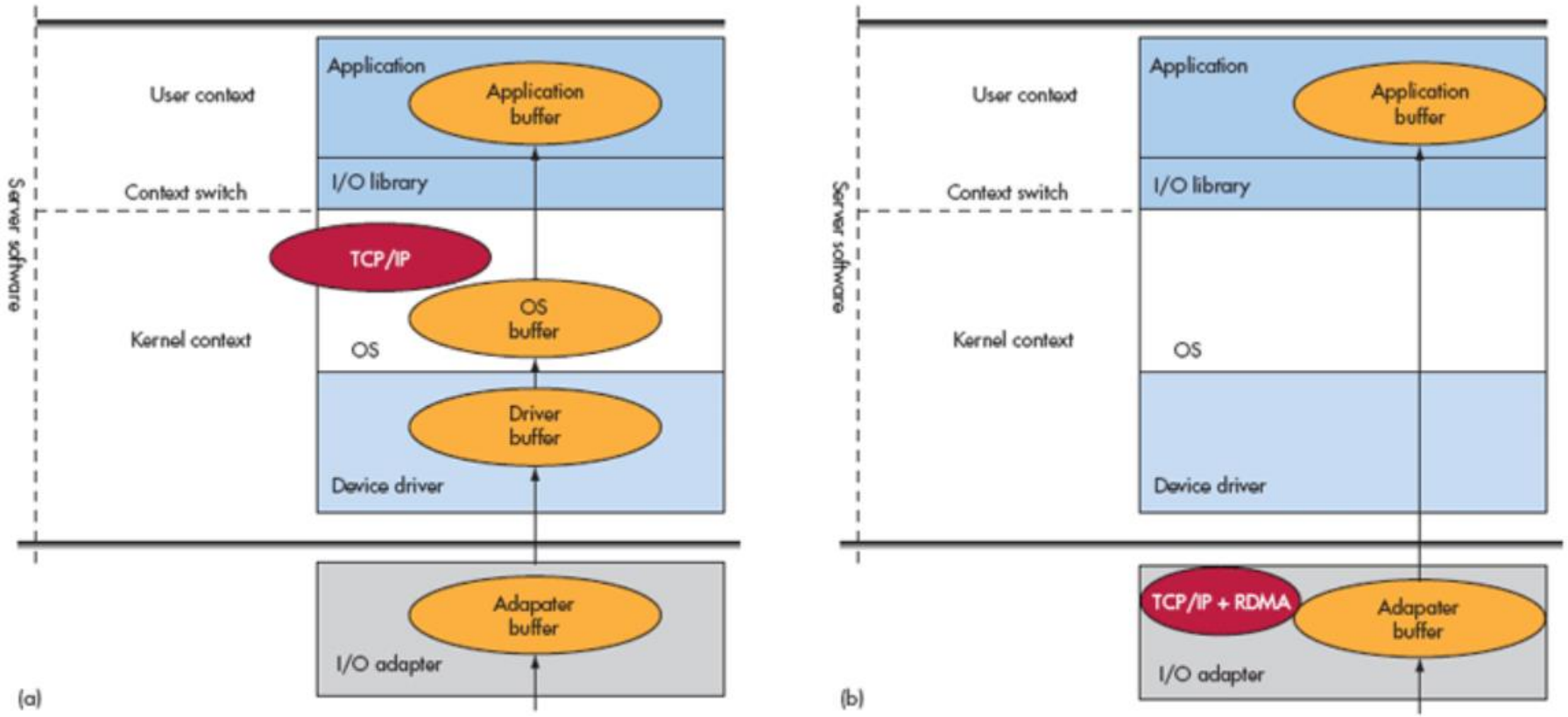
Motivation…

Hybrid Solution

- Shared memory communication latencies are low
  - *Varies between 1 – 2 us*
- RDMA communication latencies are low
  - In the range of *1 – 3 us*

Packet Size	Protocol	Localhost	Inter-machine
64 B	IB	0.9 us	2.9 us
	TCP	20.0 us	230.0 us
	PACS	0.9 us	N/A
8 KB	IB	4.7 us	7.3 us
	TCP	20.0 us	400.0 us
	PACS	1-2 us	N/A

RDMA Transfer Map



Interoperability Laboratory &Computer Science Department University of New Hampshire

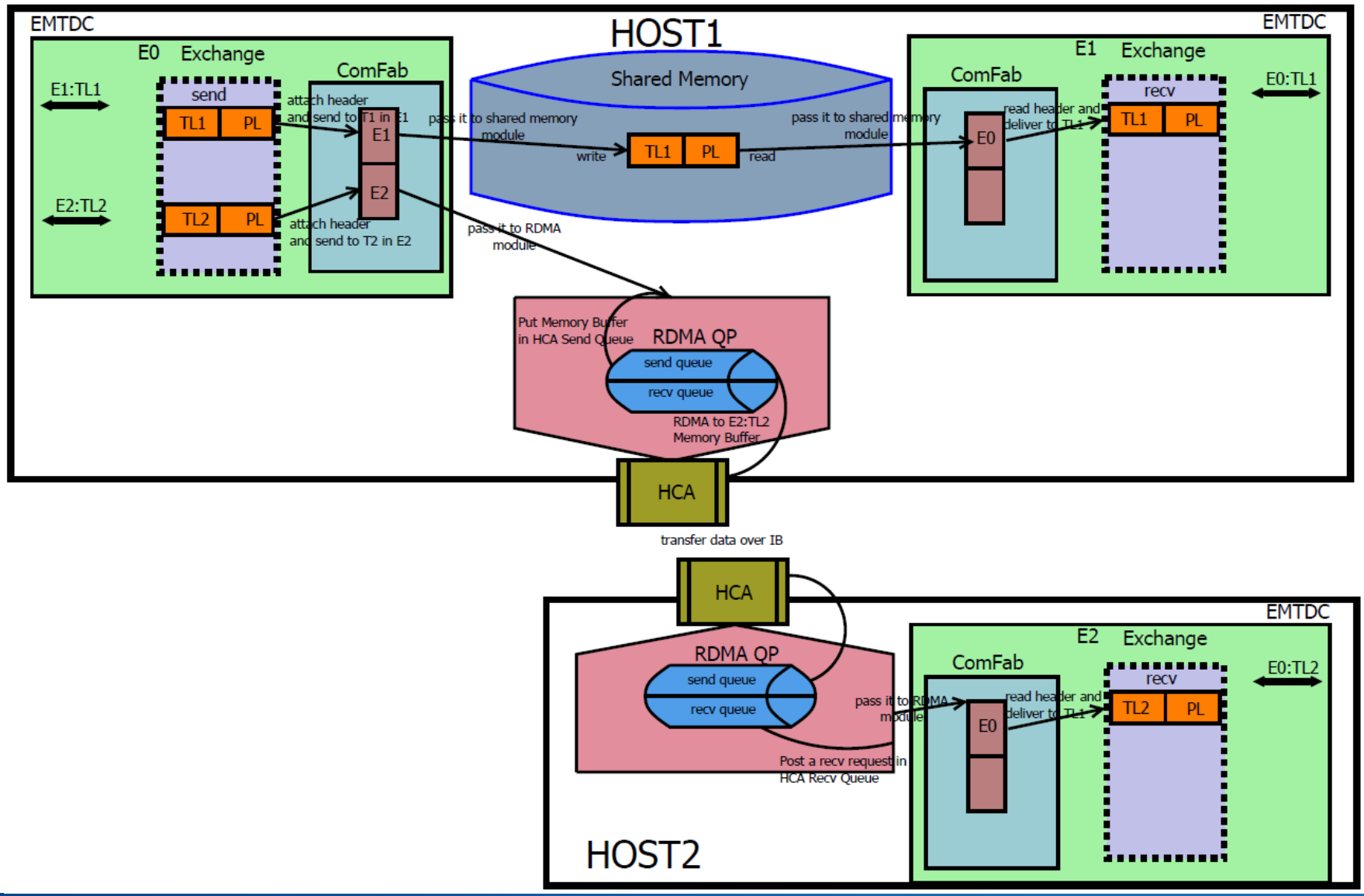
InfiniBand Speed

Performance of InfiniBand

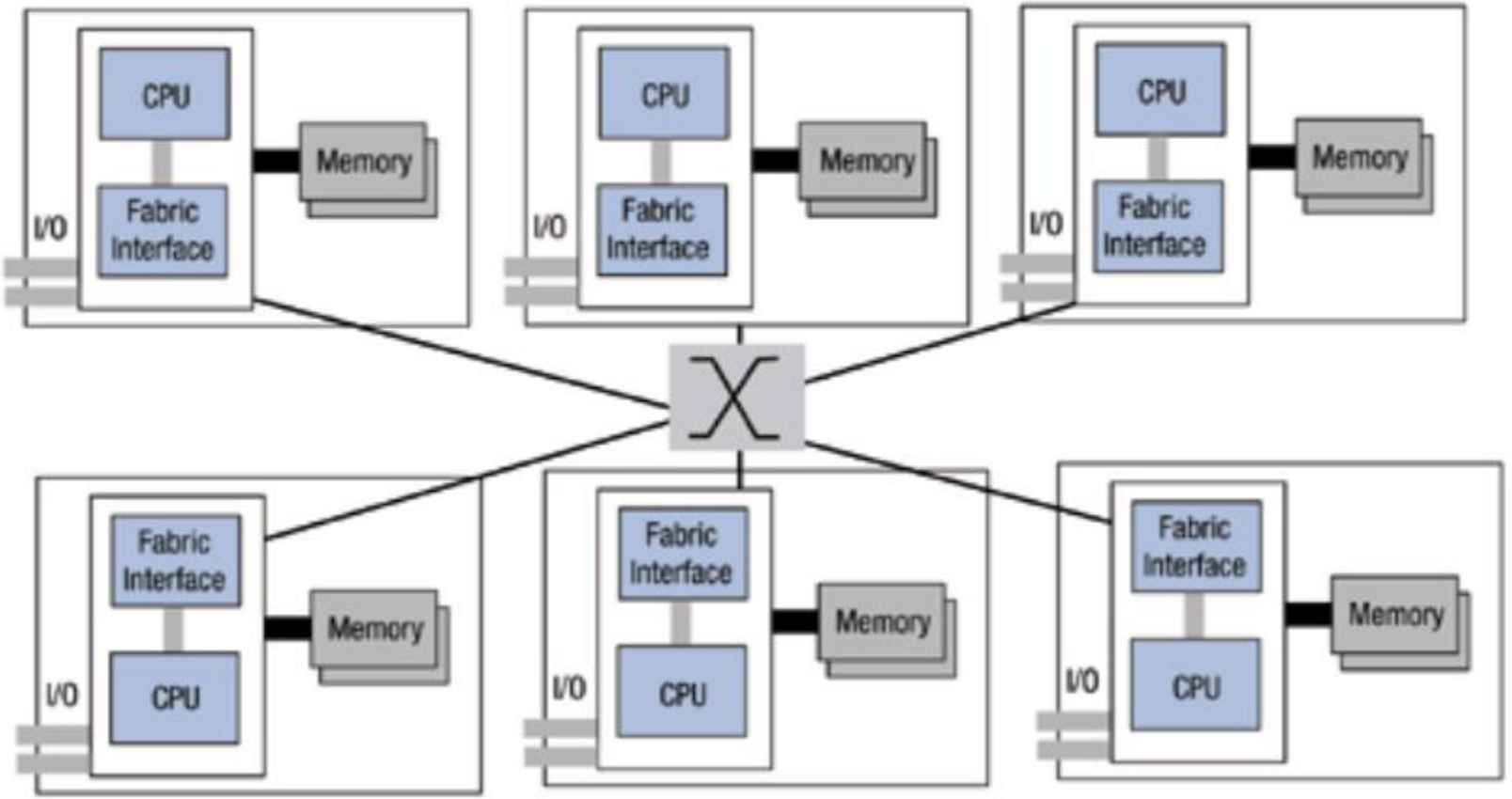
- Port to Port communication latency is 0.19 us using the IB fabric with node-node latency around 1-2 us.
- TCP/IP can range between 20-200 us
- The performance tests show that messages of size 64 bytes exchanged between server and client over IB network using RDMA gives an average latency of ~2 us

Performance verified on a Mellanox 2-node IB cluster using RDMA

Advanced Communication Fabric

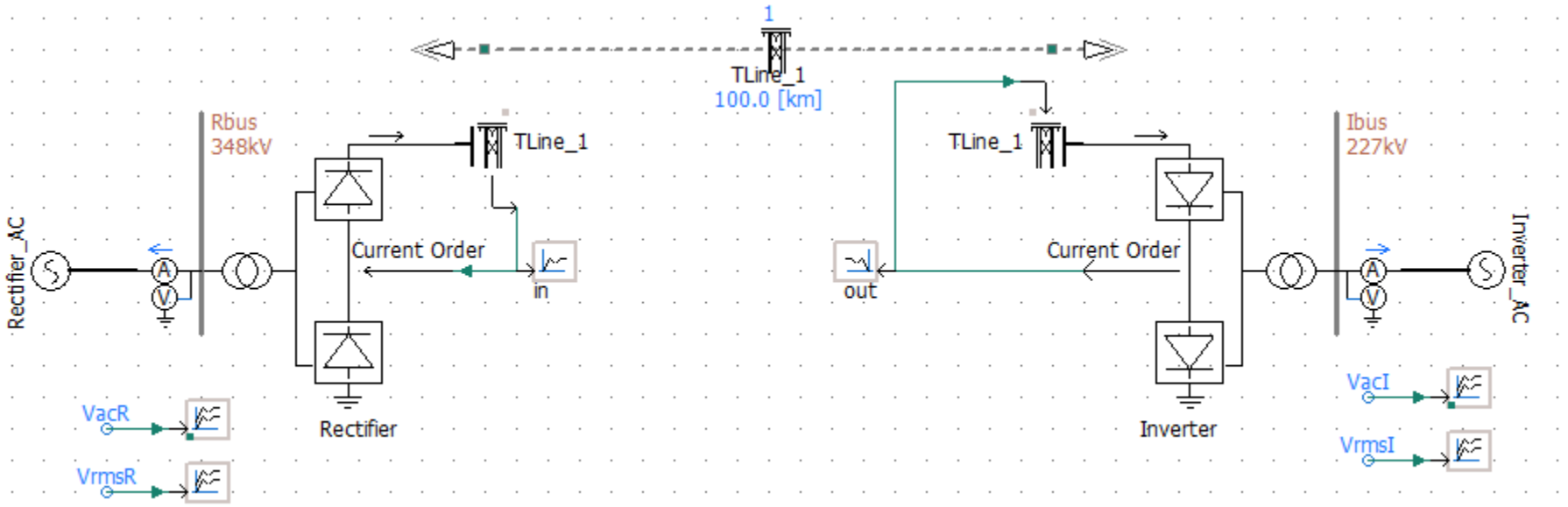


Multi-Node Fabric Architecture



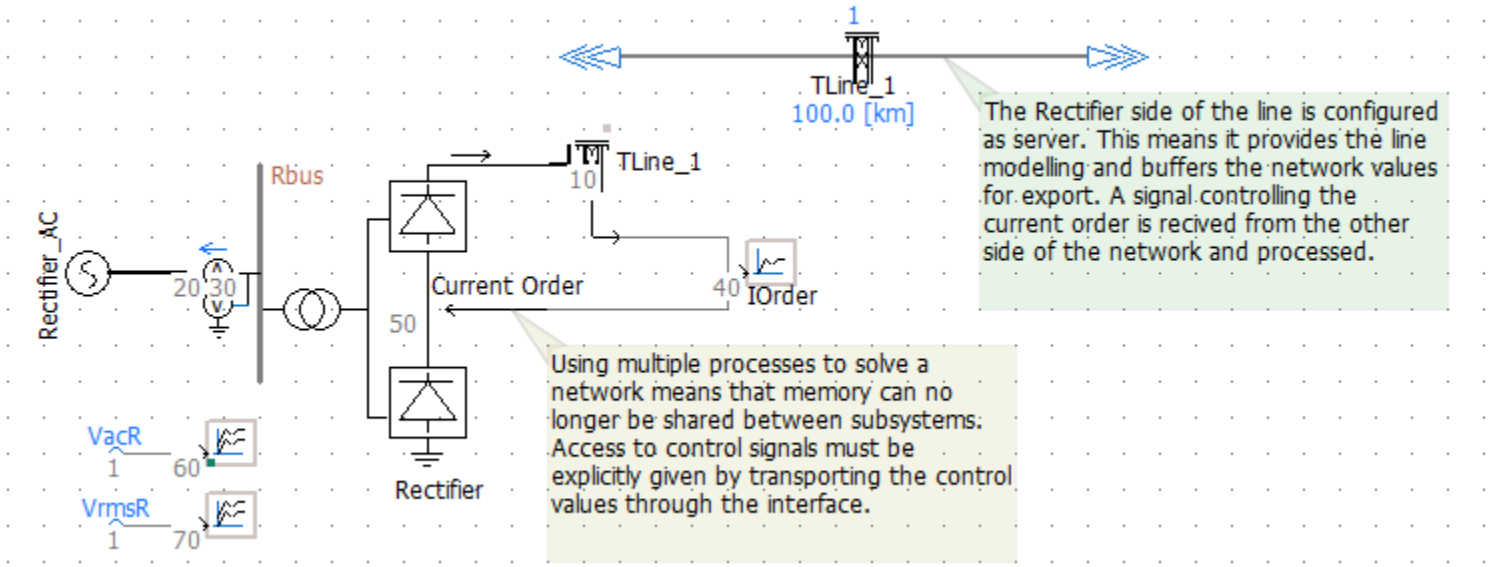
Switched Fabric Architecture for De-Centralized Computing Cluster

Experiment Split DC Link (all-in-one)



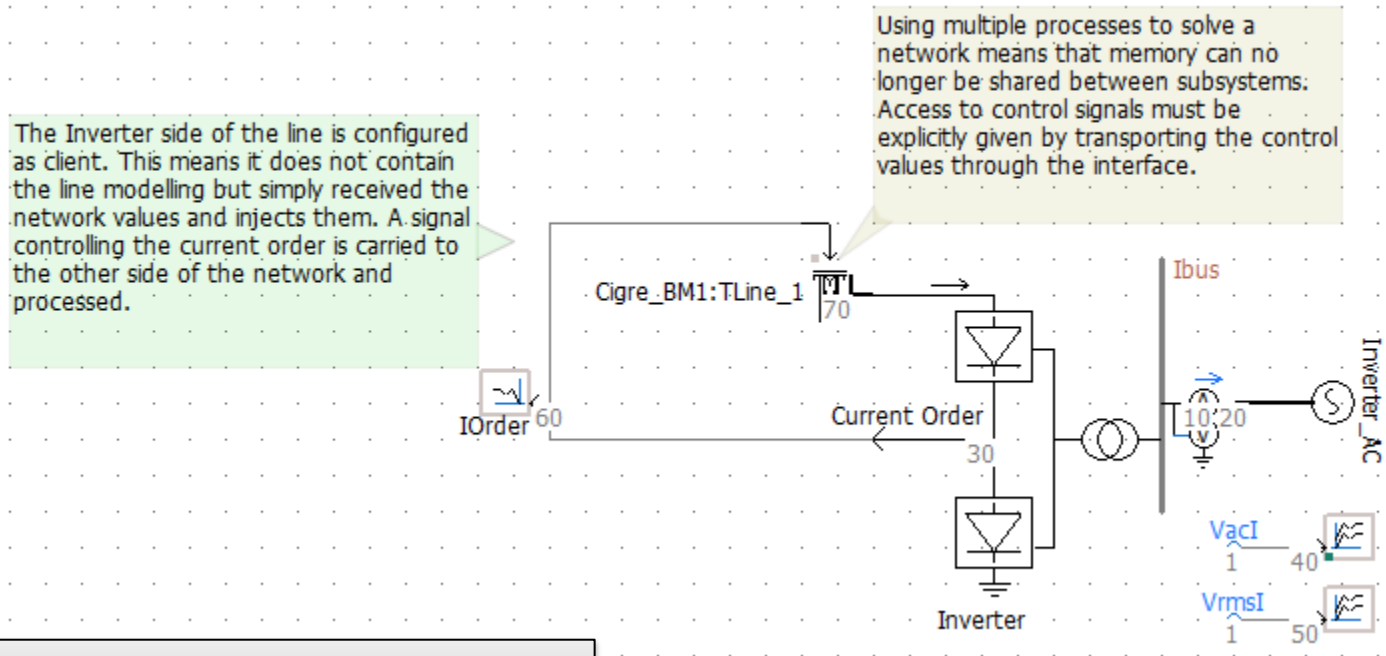
Monopolar HVDC Link representing a balanced pairing

Experiment Split DC Link (server)



On the server side, the transmission line modeling is included. For this reason the actual line configuration is included.

Experiment Split DC Link (client)



On the client side the distributed line model is not modeled since this is already taken into consideration on the server side.

Experimental Split Trivial Model

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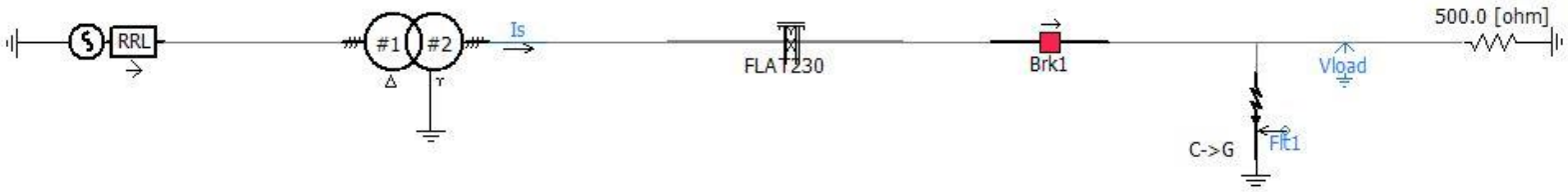
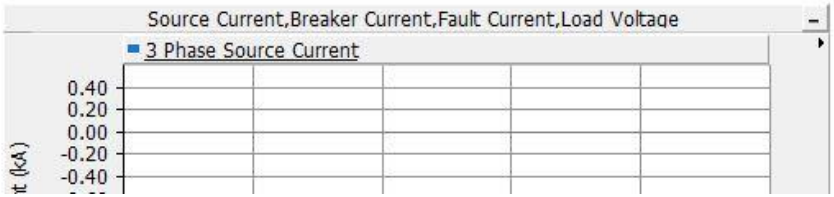
A SIMPLE AC SYSTEM

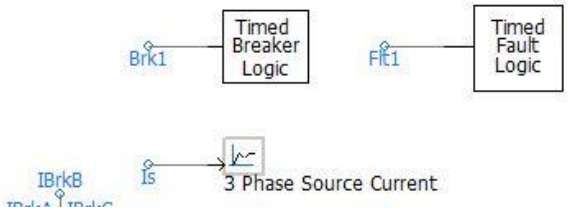
A 230 kV transmission line system with a passive load. This demonstrates the use of the single line Bergeron model of a transmission line directly connected with the sending and receiving ends as opposed to subpages in simpleac.psc and simpleac_sld1.psc. Double click on FLAT230 to see the basic parameters of the transmission line, go to 'Edit' to see more.

The sending end currents are measured on the transformer secondary windings inside the transformer component.

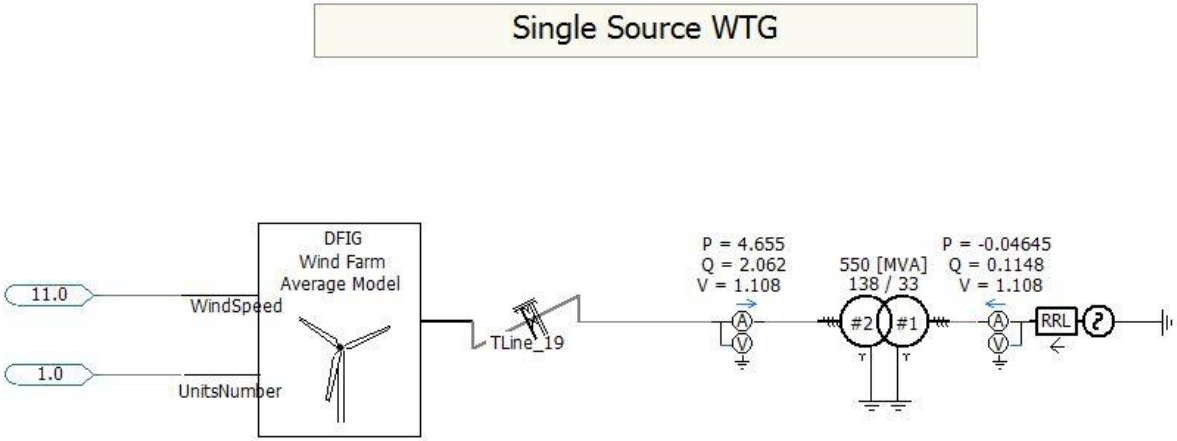
A timed phase C to ground fault is applied at 0.25 secs and lasts 50 msec. The timed breaker logic is set to trip at 0.26 secs and reconnect at 0.31 secs.



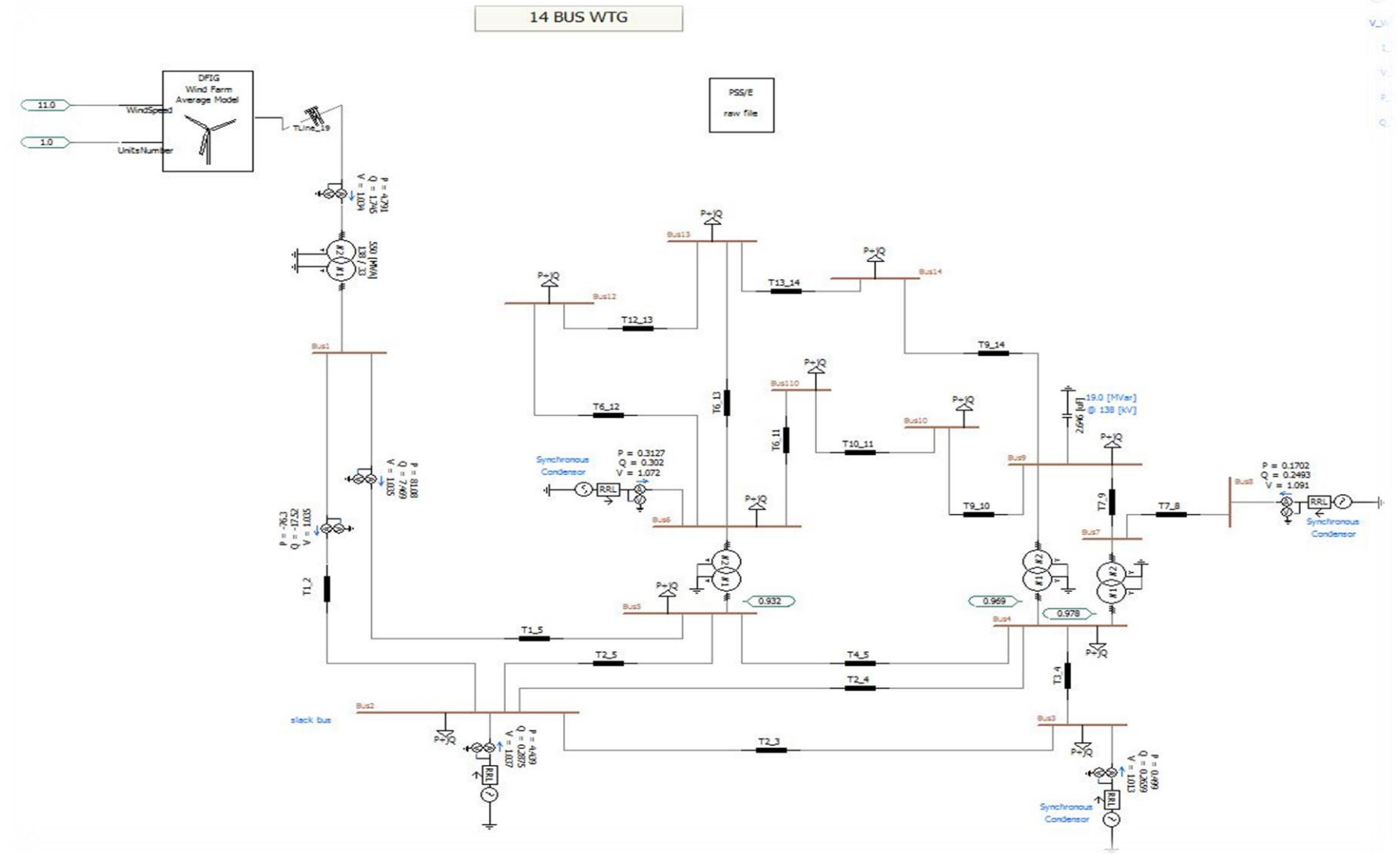




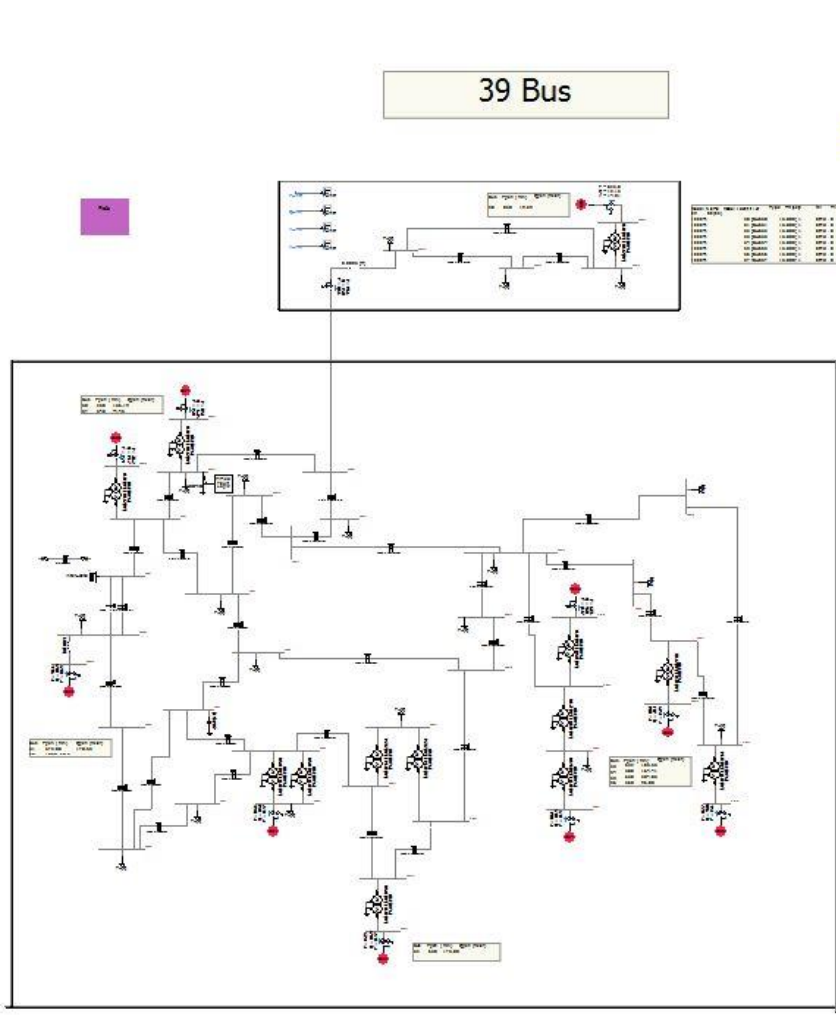
Experimental Single Split

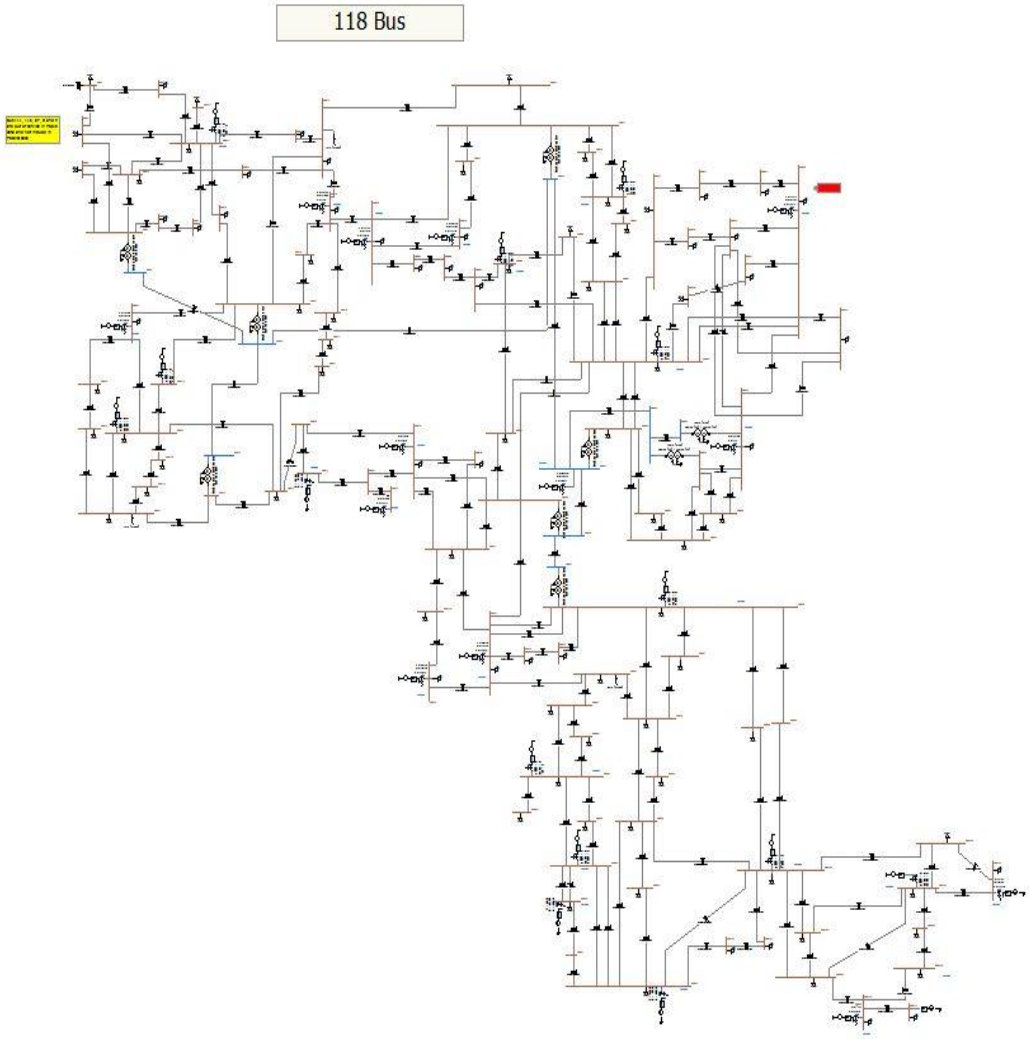


Experimental Mixed VG Network

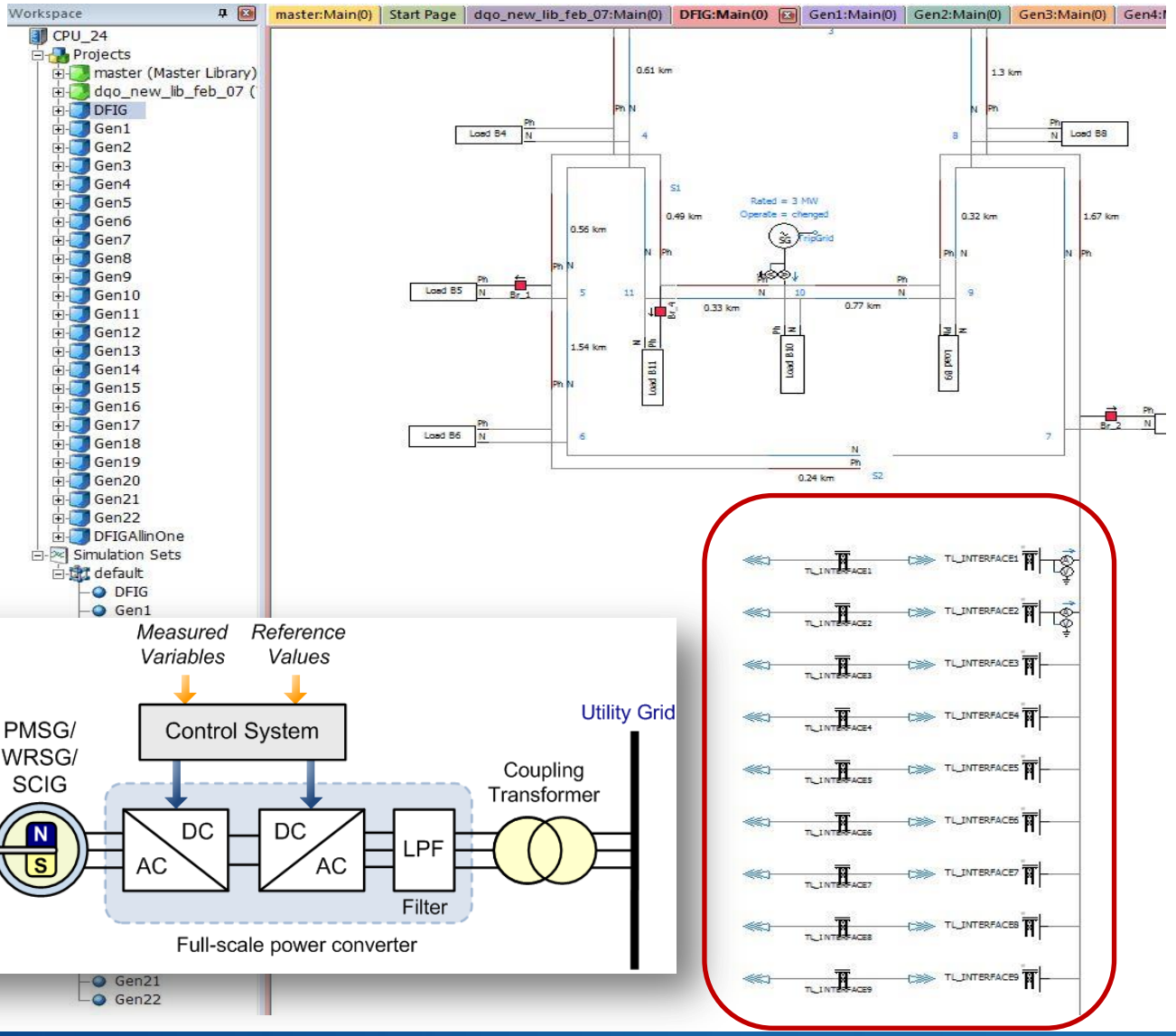


Experimental Mixed AC Network

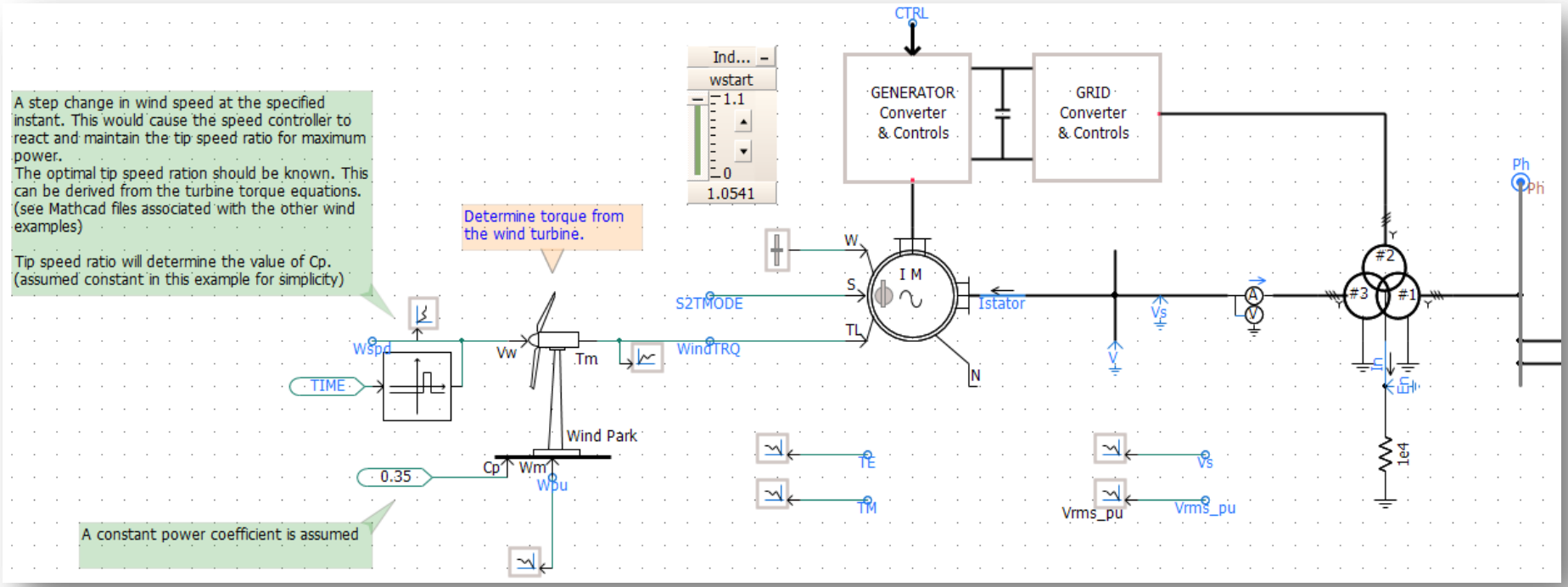




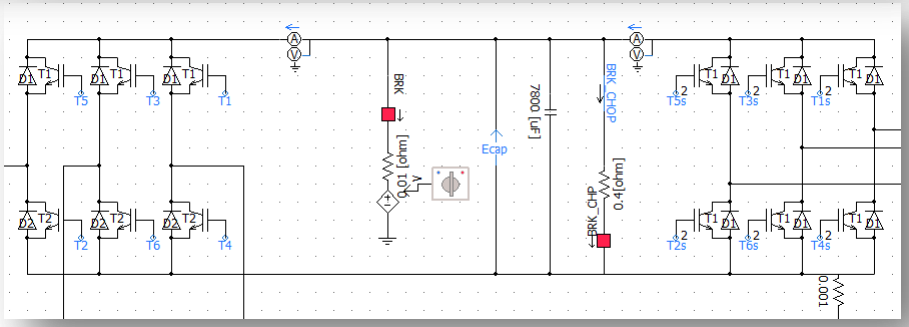
Experimental Wind Park



DFIG Machine Modeling



Each machine is modelled in full detail with complete control and protections systems. Wind speed is converted to torque on them machine based on standard specifications. Back to back converters are modeled in full detail.



Experimental Results

1 Million Communications

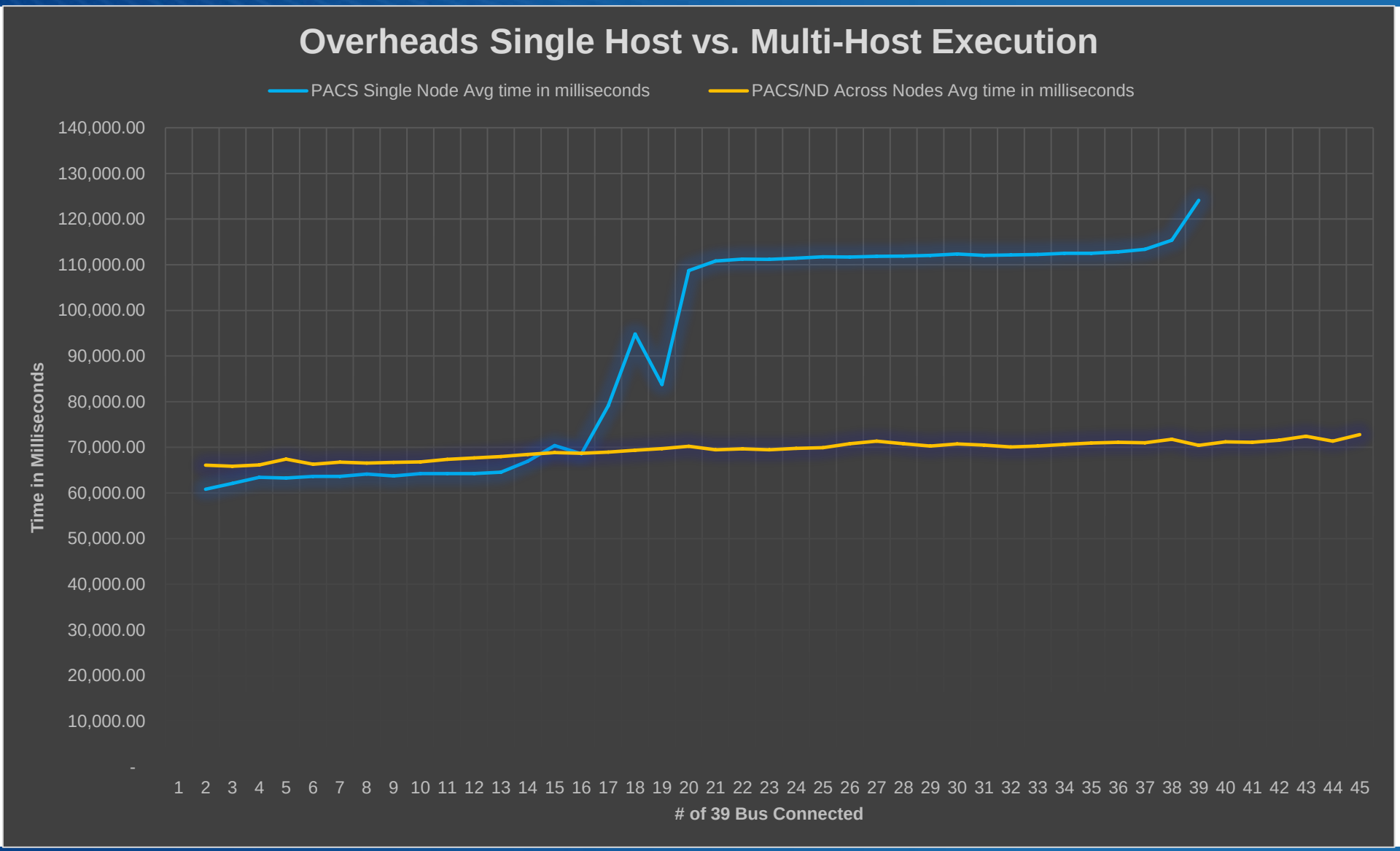
Case Name	All-in-one Single Process (sec)	Protocol	Single Node Localhost (sec)	Multi-Node Across Hosts (sec)
Simple AC Network	4	IB	--	5
		PACS	4	--
		TCP	15	252
P2P HVDC (CIGRE Benchmark)	21	IB	--	17
		PACS	15	--
		TCP	30	242
Source to Wind Park Average Model	48	IB	--	48
		PACS	44	--
		TCP	60	236
14 BUS to Wind Park Average Model	82	IB	--	52
		PACS	51	--
		TCP	62	232
39 BUS to 118 BUS	320	IB	--	188
		PACS	210	--
		TCP	224	332

Experimental Results

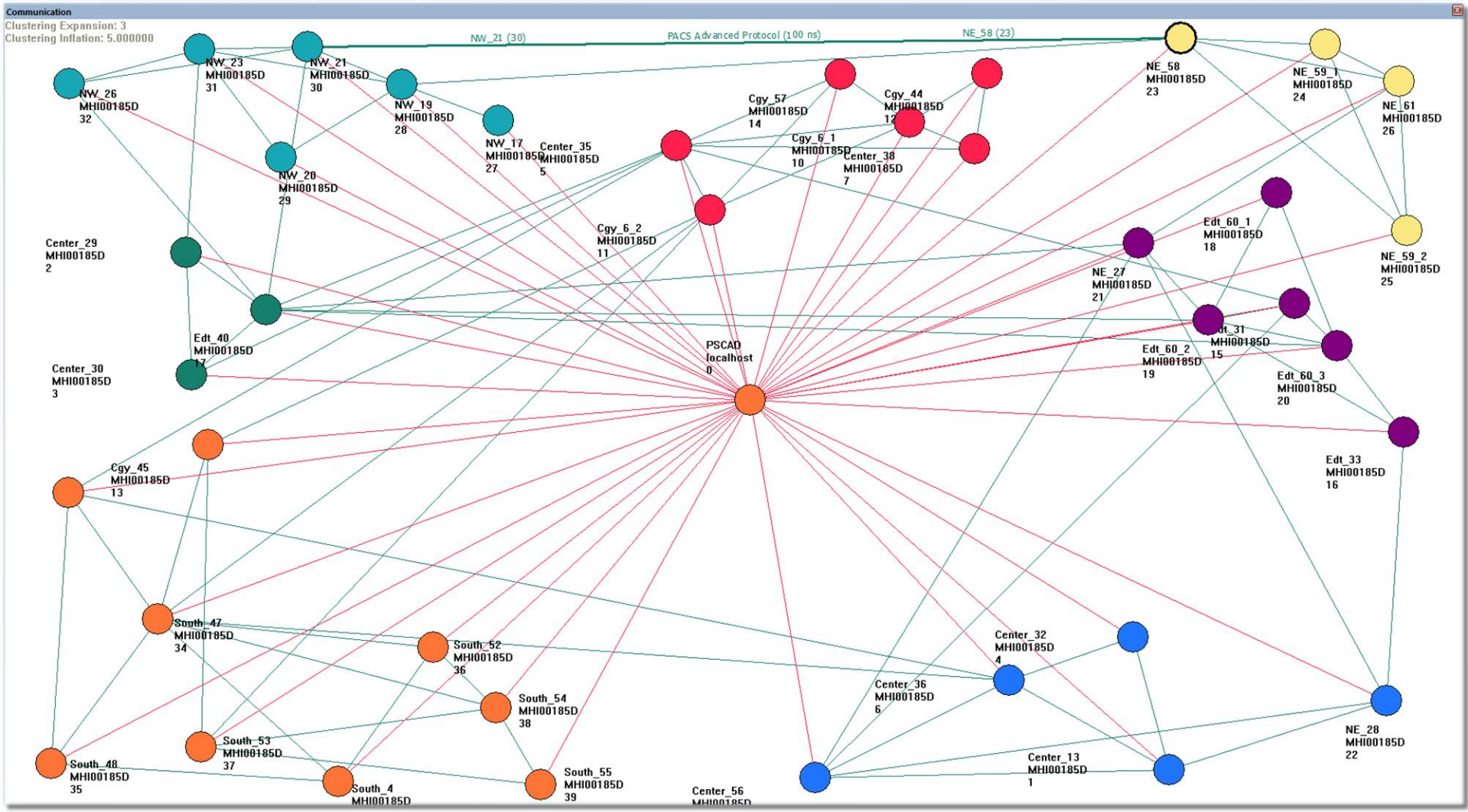
1 Million Communications

Case Name	All-in-one (sec)	Protocol	PSCAD Localhost (sec)	PSCAD Across Hosts (sec)
Wind Park Type 3 DFIG x10	679	IB	--	130
		PACS	117	--
		TCP	195	1570
Wind Park Type 3 DFIG x22	1017	IB	--	214
		PACS	160	--
		TCP	319	1827
Wind Park Type 3 DFIG x38	1850	IB	--	270
		PACS	259	--
		TCP	587	2127
2500 Bus Transmission Network (40 splits)	18206	IB	--	**410** (x44)**
		PACS	**604** (x30)**	--
		TCP	1520 (x12)	838 (x21)

Experiment Results

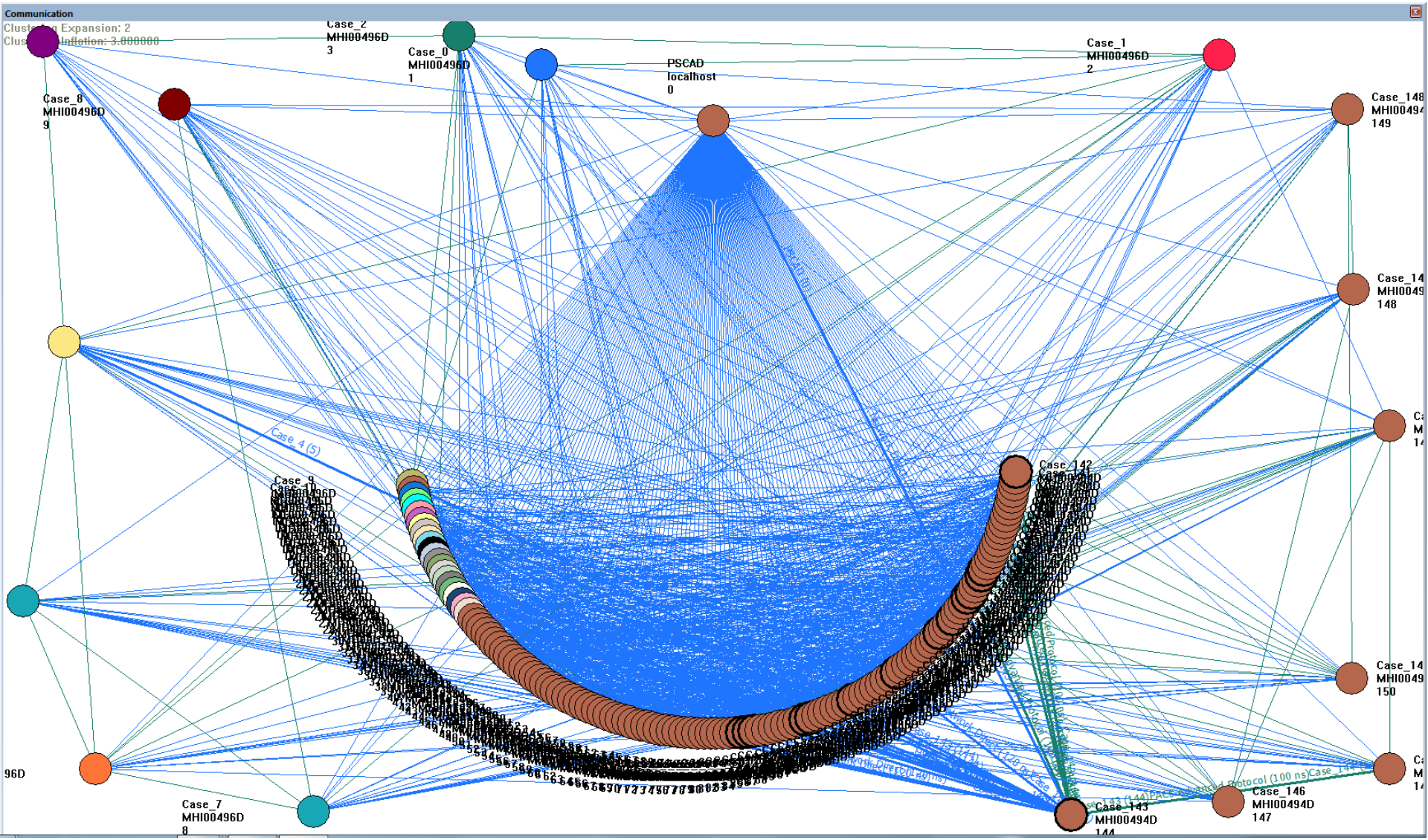


MCL Application and View



Markov Chain Clustering Algorithm (MCL) applied to 40 Way Concurrent EMTDC.

150 Way Split of Across 4 Nodes



Future Targets

Breaking large power system simulation into smaller tasks is difficult

- Inherent inter-dependence in mesh configuration
- Breaks reduce computational burden per process, but increase number of processes and interconnects
- Optimally mapping large number of broken apart sub-networks onto a fixed number of processors is challenging
- Intelligent graph theory methods may be required to
  - Optimize loading on processes
  - Optimize the use of processors

Conclusions

- High Performance Communication Fabric Advantages
  - Conventional TCP/IP kernel overheads limit scaling.
  - Zero mutex IPC with shared ring buffers offers exceptionally low latency.
  - IP over IB offers nearly the same performance as local shared memory.
  - Processor affinity can be maintained using non-blocking methods.
  - Separating the communication fabric provides portability
  - Co-simulation can be achieved by matching message protocols.
  - Sub-synchronous interactions studies possible with full fidelity simulations.

MANITOBA·HVDC RESEARCH CENTRE

Thank you!