NS-3 Tutorial

Tom Henderson (University of Washington and Boeing Research & Technology)
Mathieu Lacage (Alcméon)

March 2013

ns-3 tutorial agenda

- 13h00-15h00: Getting started with ns-3
  - Overview of software and models
  - Basic structure of the core and important models
  - Running and understanding an existing example
  - Animation and visualization
- 15h00-15h30: 30-minute coffee break
- 15h30-17h00: Going further with ns-3
  - Writing and debugging your own examples
  - Integrating other tools and libraries
  - Parallel simulations
  - Emulation, virtual machine and testbed integration
  - Getting help and getting involved

Preliminaries

- ns-3 is written in C++, with bindings available for Python
  - simulation programs are C++ executables or Python programs
  - ~300,000 lines of mostly C++ (estimate based on cloc source code analysis)
- ns-3 is a GNU GPLv2-licensed project
- ns-3 is mainly supported for Linux, OS X, and FreeBSD
- ns-3 is not backwards-compatible with ns-2

Preliminaries (cont.)

- Where do I get ns-3?
  - http://www.nsnam.org
- Where do I get today's code?
  - http://www.nsnam.org/release/ns-allinone-3.16.tar.bz2

What have people done with ns-3?

- ~300 publications to date
  - search of 'ns-3 simulator' on IEEE and ACM digital libraries

1814 IEEE/ACM TRANSACTIONS ON NETWORKING, VOL. 20, NO. 6, DECEMBER 2012

FSR: Formal Analysis and Implementation Toolkit for Safe Interdomain Routing

Anduo Wang, Limin Jia, *Member, IEEE*, Wenchao Zhou, Yiqing Ren, Boon Thau Loo, Jennifer Rexford, *Senior Member, IEEE*, Vivek Nigam, Andre Scedrov, and Carolyn Talcott

Abstract—Interdomain routing stitches the disparate parts of the Internet together, making protocol stability a critical issue to both researchers and practitioners. Yet, researchers create safety proofs and counterexamples by hand and build simulators and prototypes to explore protocol dynamics. Similarly, network operators analyze their router configurations manually or using homegrown tools. In this paper, we present a comprehensive toolkit for analyzing and implementing routing policies, ranging from high-level guidelines to specific router configurations. Our Formally Safe Routing (*FSR*) toolkit performs all of these functions from the same algebraic representation of routing policy. We show that routing algebra has a natural translation to both *integer constraints* (to perform safety analysis with SMT solvers) and *declarative programs* (to generate distributed implementations). Our extensive experiments with realistic topologies and policies show how *FSR* can detect problems in an autonomous system's (AS's) BGP configuration, prove sufficient conditions for Border Gateway Protocol (BGP) safety, and empirically evaluate convergence time.

Index Terms—Communications technology, declarative networking, formal analysis, routing algebra.

I. Introduction

THE INTERNET'S global routing system does not necessarily converge, depending on how the Border Gateway Protocol (BGP) policies of individual networks are configured. Since protocol oscillations cause serious performance disruptions and router overhead, researchers devote significant attention to BGP stability (or "safety"). Abstract formal models of BGP [12]–[15], [36] allow researchers to explore how local policies affect BGP stability and identify policy guidelines that, if universally adopted by ISPs, ensure global safety [4], [8]–[11], [33]. While our understanding of BGP safety has improved dramatically in the past decade, each research study still proceeds independently—manually creating proofs and counterexamples, and sometimes building simulators or prototypes to study protocol overhead and transient behavior during convergence.

To aid the design, analysis, and evaluation of safe interdomain routing, we propose the *Formally Safe Routing* (*FSR*) toolkit. *FSR* serves two important communities. For researchers, *FSR* automates important parts of the design process and provides a common framework for describing, evaluating, and comparing new safety guidelines. For network operators, *FSR* automates the analysis of internal router (iBGP) and border gateway (eBGP) configurations for safety violations. For both communities, *FSR* automatically generates realistic protocol implementations to evaluate real network configurations (e.g., to study convergence time) prior to actual deployment. The ideas underlying *FSR* also unify research in *routing algebras* [13], [36] with recent advances in *declarative networking* [22] to produce provably correct implementations of safe interdomain routing.

Given policy configurations as input, *FSR* produces an analysis of safety properties and a distributed protocol implementation, as shown in Fig. 1. *FSR* has three main underlying technologies.

- *Policy configuration as algebra:* Our extensions to routing algebra [13], [36] allow researchers and network operators to express policy configurations in an abstract algebraic form. These configurations can be anything from high-level *policy guidelines* (e.g., proposed constraints that a researcher wants to study) or a completely specified *policy instance* [e.g., an iBGP configuration or a multi-autonomous-system (AS) network that an operator wants to analyze]. Router configuration files can be automatically translated into the algebraic representation, easing the adoption of *FSR*.
- *Safety analysis:* To automatically analyze the policy configuration, *FSR* reduces the convergence proof to a

Policy Configurations

Routing Mechanism (Path-vector)

Declarative Networking Engine

SMT Solver (Yices)

Safety Requirement (Strict Monotonicity)

Distributed Implementation

Safety Analysis Result

Fig. 1. *FSR* architecture.

Manuscript received May 23, 2011; accepted January 21, 2012; approved by IEEE/ACM TRANSACTIONS ON NETWORKING Editor Z. M. Mao. Date of publication March 14, 2012; date of current version December 13, 2012. This work was supported in part by the NSF under Grants CCF-0820208, CNS-0830949, CNS-0845552, CNS-1040672, CPS-0931871, IIS-0812270, and TC-0905607; the AFOSR under Grants FA9550-08-1-0352 and FA9550-09-1-0643; the ONR under Grants N00014-09-1-0770 and N00014-11-1-0555; a gift from Cisco System; and the A. von Humboldt Foundation.

A. Wang, W. Zhou, Y. Ren, B. T. Loo, and A. Scedrov are with the University of Pennsylvania, Philadelphia, PA 19104 USA (e-mail: anduo@seas.upenn.edu; wenchaoz@seas.upenn.edu; yiqing@seas.upenn.edu; boonloo@seas.upenn.edu; scedrov@math.upenn.edu).

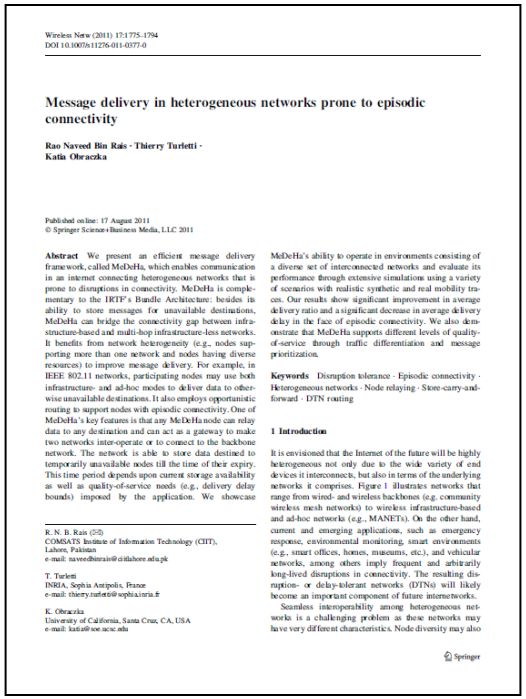
L. Jia is with Carnegie Mellon University, Pittsburgh, PA 15213 USA (e-mail: liminjia@cmu.edu).

J. Rexford is with Princeton University, Princeton, NJ 08540 USA (e-mail: jrex@cs.princeton.edu).

V. Nigam is with the Computer Science Department, Ludwig-Maximilians University of Munich, Munich 80539, Germany.

C. Talcott is with the SRI International, Menlo Park, CA 94025 USA (e-mail: clt@csl.sri.com).

Digital Object Identifier 10.1109/TNET.2012.2187924



Wireless Netw (2011) 17:1775–1794
DOI 10.1007/s11276-011-0377-0

Message delivery in heterogeneous networks prone to episodic connectivity

Rao Naveed Bin Rais · Thierry Turletti · Katia Obraczka

Published online: 17 August 2011

Abstract We present an efficient message delivery framework, called MeDeHa, which enables communication in an internet connecting heterogeneous networks that is prone to disruptions in connectivity. MeDeHa is complementary to the IRTF's Bundle Architecture: besides its ability to store messages for unavailable destinations, MeDeHa can bridge the connectivity gap between infrastructure-based and multi-hop infrastructure-less networks. It benefits from network heterogeneity (e.g., nodes supporting more than one network and nodes having diverse resources) to improve message delivery. For example, in IEEE 802.11 networks, participating nodes may use both infrastructure- and ad-hoc modes to deliver data to otherwise unavailable destinations. It also employs opportunistic routing to support nodes with episodic connectivity. One of MeDeHa's key features is that any MeDeHa node can relay data to any destination and can act as a gateway to make two networks inter-operate or to connect to the backbone network. The network is able to store data destined to temporarily unavailable nodes till the time of their expiry. This time period depends upon current storage availability as well as quality-of-service needs (e.g., delivery delay bounds) imposed by the application. We showcase MeDeHa's ability to operate in environments consisting of a diverse set of interconnected networks and evaluate its performance through extensive simulations using a variety of scenarios with realistic synthetic and real mobility traces. Our results show significant improvement in average delivery ratio and a significant decrease in average delivery delay in the face of episodic connectivity. We also demonstrate that MeDeHa supports different levels of quality-of-service through traffic differentiation and message prioritization.

Keywords Disruption tolerance · Episodic connectivity · Heterogeneous networks · Node relaying · Store-carry-and-forward · DTN routing

1 Introduction

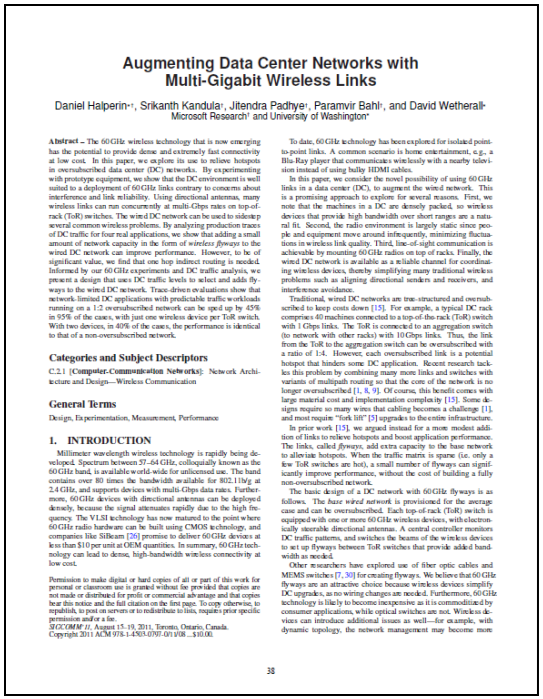
It is envisioned that the Internet of the future will be highly heterogeneous not only due to the wide variety of end devices it interconnects, but also in terms of the underlying networks it comprises. Figure 1 illustrates networks that range from wired- and wireless backbones (e.g. community wireless mesh networks) to wireless infrastructure-based and ad-hoc networks (e.g., MANETs). On the other hand, current and emerging applications, such as emergency response, environmental monitoring, smart environments (e.g., smart offices, homes, museums, etc.), and vehicular networks, among others imply frequent and arbitrarily long-lived disruptions in connectivity. The resulting disruption- or delay-tolerant networks (DTNs) will likely become an important component of future internetworks.

Seamless interoperability among heterogeneous networks is a challenging problem as these networks may have very different characteristics. Node diversity may also

R. N. B. Rais (✉)
COMSATS Institute of Information Technology (CIIT), Lahore, Pakistan
e-mail: naveedbinrais@ciitlahore.edu.pk

T. Turletti
INRIA, Sophia Antipolis, France
e-mail: thierry.turletti@sophia.inria.fr

K. Obraczka
University of California, Santa Cruz, CA, USA
e-mail: katia@soe.ucsc.edu



Augmenting Data Center Networks with Multi-Gigabit Wireless Links

Daniel Halperin*†, Srikanth Kandula†, Jitendra Padhye†, Paramvir Bahl†, and David Wetherall‡
Microsoft Research† and University of Washington*

Abstract – The 60 GHz wireless technology that is now emerging has the potential to provide dense and extremely fast connectivity at low cost. In this paper, we explore its use to relieve hotspots in oversubscribed data center (DC) networks. By experimenting with prototype equipment, we show that the DC environment is well suited to a deployment of 60 GHz links contrary to concerns about interference and link reliability. Using directional antennas, many wireless links can run concurrently at multi-Gbps rates on top-of-rack (ToR) switches. The wired DC network can be used to sidestep several common wireless problems. By analyzing production traces of DC traffic for four real applications, we show that adding a small amount of network capacity in the form of *wireless flyways* to the wired DC network can improve performance. However, to be of significant value, we find that one hop indirect routing is needed. Informed by our 60 GHz experiments and DC traffic analysis, we present a design that uses DC traffic levels to select and adds flyways to the wired DC network. Trace-driven evaluations show that network-limited DC applications with predictable traffic workloads running on a 1:2 oversubscribed network can be sped up by 45% in 95% of the cases, with just one wireless device per ToR switch. With two devices, in 40% of the cases, the performance is identical to that of a non-oversubscribed network.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—Wireless Communication

General Terms

Design, Experimentation, Measurement, Performance

1. INTRODUCTION

Millimeter wavelength wireless technology is rapidly being developed. Spectrum between 57–64 GHz, colloquially known as the 60 GHz band, is available world-wide for unlicensed use. The band contains over 80 times the bandwidth available for 802.11b/g at 2.4 GHz, and supports devices with multi-Gbps data rates. Furthermore, 60 GHz devices with directional antennas can be deployed densely, because the signal attenuates rapidly due to the high frequency. The VLSI technology has now matured to the point where 60 GHz radio hardware can be built using CMOS technology, and companies like Silicam [26] promise to deliver 60 GHz devices at less than $10 per unit at OEM quantities. In summary, 60 GHz technology can lead to dense, high-bandwidth wireless connectivity at low cost.

SIGCOMM'11, August 15–19, 2011, Toronto, Ontario, Canada.

To date, 60 GHz technology has been explored for isolated point-to-point links. A common scenario is home entertainment, e.g., a Blu-Ray player that communicates wirelessly with a nearby television instead of using bulky HDMI cables.

In this paper, we consider the novel possibility of using 60 GHz links in a data center (DC), to augment the wired network. This is a promising approach to explore for several reasons. First, we note that the machines in a DC are densely packed, so wireless devices that provide high bandwidth over short ranges are a natural fit. Second, the radio environment is largely static since people and equipment move around infrequently, minimizing fluctuations in wireless link quality. Third, line-of-sight communication is achievable by mounting 60 GHz radios on top of racks. Finally, the wired DC network is available as a reliable channel for coordinating wireless devices, thereby simplifying many traditional wireless problems such as aligning directional senders and receivers, and interference avoidance.

Traditional, wired DC networks are tree-structured and oversubscribed to keep costs down [15]. For example, a typical DC rack comprises 40 machines connected to a top-of-the-rack (ToR) switch with 1 Gbps links. The ToR is connected to an aggregation switch (to network with other racks) with 10 Gbps links. Thus, the link from the ToR to the aggregation switch can be oversubscribed with a ratio of 1:4. However, each oversubscribed link is a potential hotspot that hinders some DC application. Recent research tackles this problem by combining many more links and switches with variants of multipath routing so that the core of the network is no longer oversubscribed [1, 8, 9]. Of course, this benefit comes with large material cost and implementation complexity [15]. Some designs require so many wires that cabling becomes a challenge [1], and most require "fork lift" [5] upgrades to the entire infrastructure.

In prior work [15], we argued instead for a more modest addition of links to relieve hotspots and boost application performance. The links, called *flyways*, add extra capacity to the base network to alleviate hotspots. When the traffic matrix is sparse (i.e. only a few ToR switches are hot), a small number of flyways can significantly improve performance, without the cost of building a fully non-oversubscribed network.

The basic design of a DC network with 60 GHz flyways is as follows. The *base wired network* is provisioned for the average case and can be oversubscribed. Each top-of-rack (ToR) switch is equipped with one or more 60 GHz wireless devices, with electronically steerable directional antennas. A central controller monitors DC traffic patterns, and switches the beams of the wireless devices to set up flyways between ToR switches that provide added bandwidth as needed.

Other researchers have explored use of fiber optic cables and MEMS switches [7, 30] for creating flyways. We believe that 60 GHz flyways are an attractive choice because wireless devices simplify DC upgrades, as no wiring changes are needed. Furthermore, 60 GHz technology is likely to become inexpensive as it is commoditized by consumer applications, while optical switches are not. Wireless devices can introduce additional issues as well—for example, with dynamic topology, the network management may become more

What have people done with ns-3?

- Educational use (from ns-3 wiki)

Using ns-3 in Education

This page is a resource for learning about ns-3 as an educational tool for networking education.

Papers

The 2011 Sigcomm Education workshop had a paper regarding ns-3 use in the classroom:

- An Open-source and Declarative Approach Towards Teaching Large-scale Networked Systems Programming

Courses using ns-3

The following courses have used ns-3 as courseware or to support projects

- Georgia Tech. ECE 6110 Dr. George Riley, Spring 2013 (also Fall 2011, Fall 2010)
- The University of Kansas EECS 780, EECS 882, and EECS 983 Dr. James Sterbenz, 2010 – 2012
- UPenn CIS 553/TCOM 512 Dr. Boon Thau Loo, Fall 2010
- Aalto University Jose Costa-Requena and Markus Peuhkuri, Fall 2011
- Indian Institute of Technology Bombay Bhaskaran Raman, Autumn 2008
- University of Rijeka
  - RM2-InfUniRi, Dr. Mario Radovan and Vedran Miletić, Spring 2013, also Spring 2012
  - RM-RiTeh, Dr. Mladen Tomić and Vedran Miletić, Spring 2013

Other resources

- Lalith Suresh's Lab Assignments using ns-3 page.

Software introduction

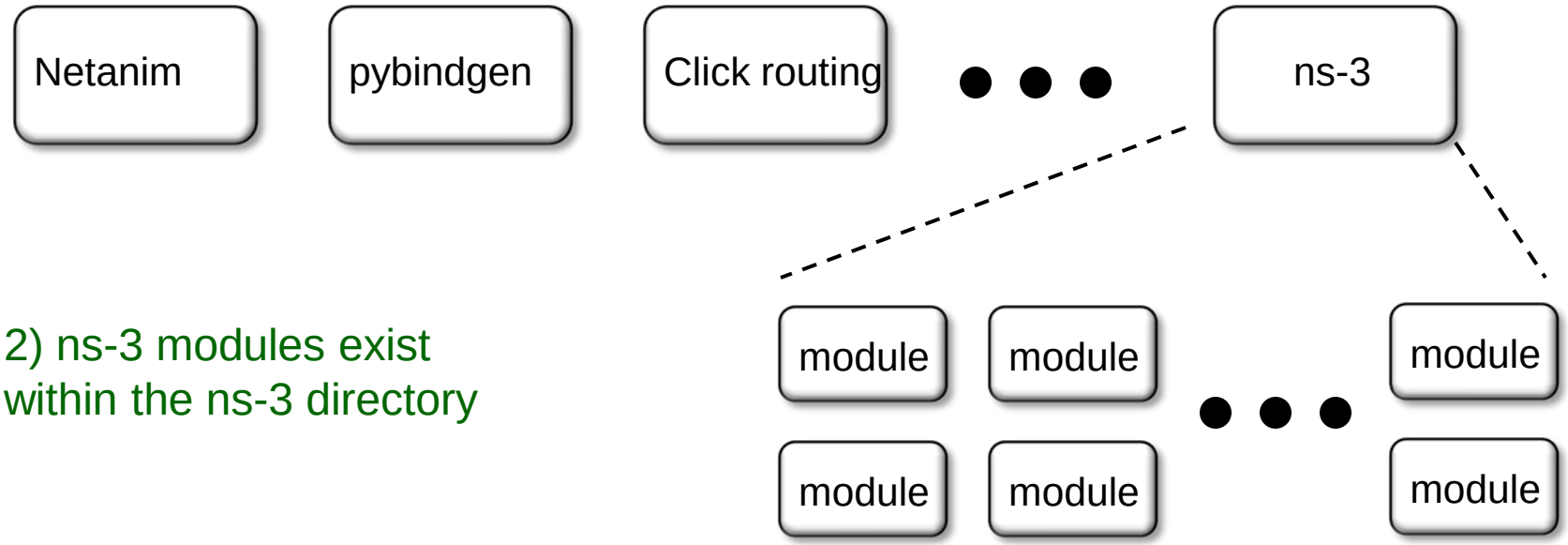
- Download the latest release
  - `wget http://www.nsnam.org/releases/ns-allinone-3.16.tar.bz2`
  - `tar xjf ns-allinone-3.16.tar.bz2`
- Clone the latest development code
  - `hg clone http://code.nsnam.org/ns-3-allinone`

Q. What is "**hg clone**"?
A. Mercurial (http://www.selenic.com) is our source code control tool.

Software organization

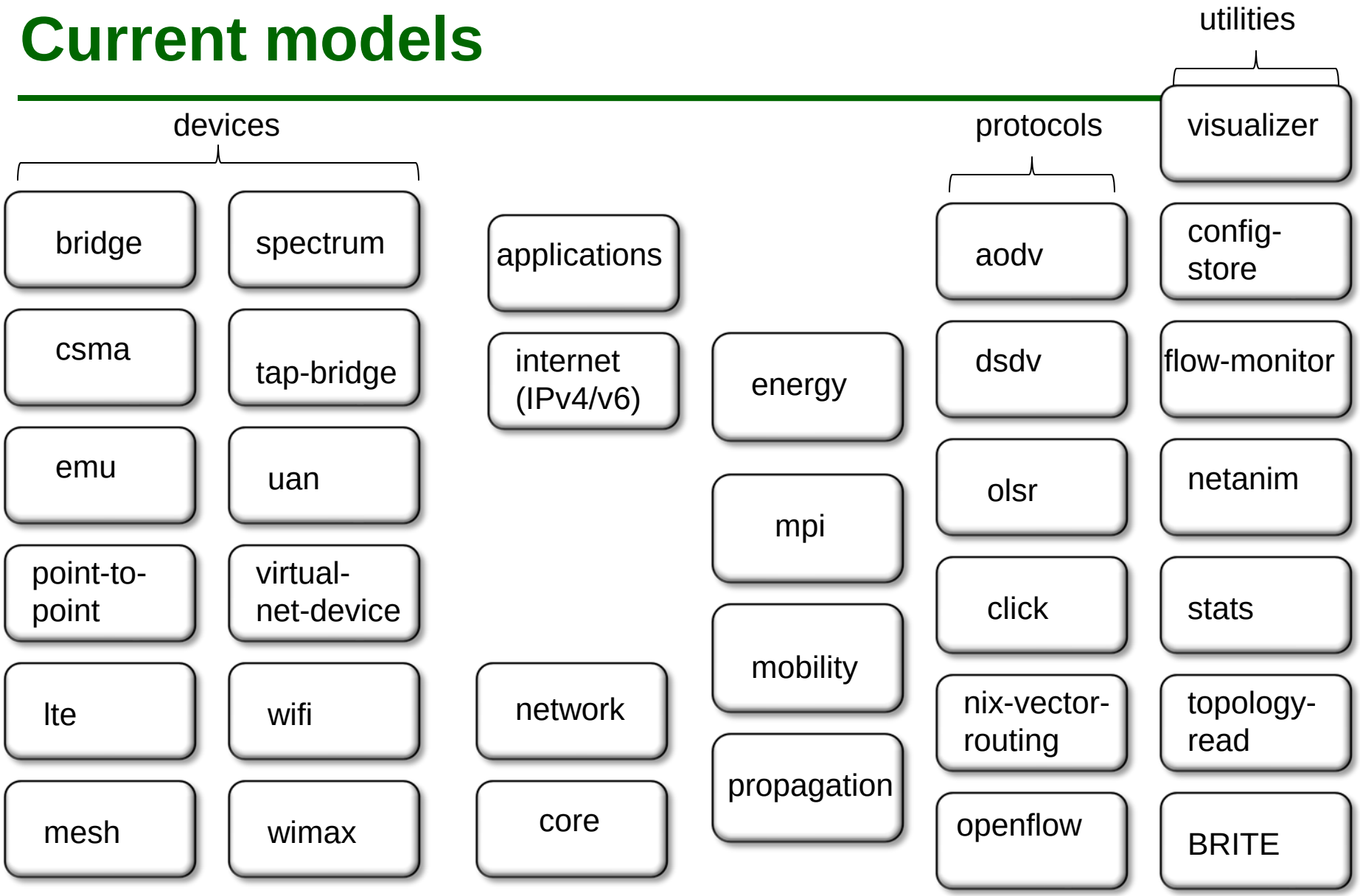
- Two levels of ns-3 software and libraries

1) Several supporting libraries, not system-installed, can be in parallel to ns-3

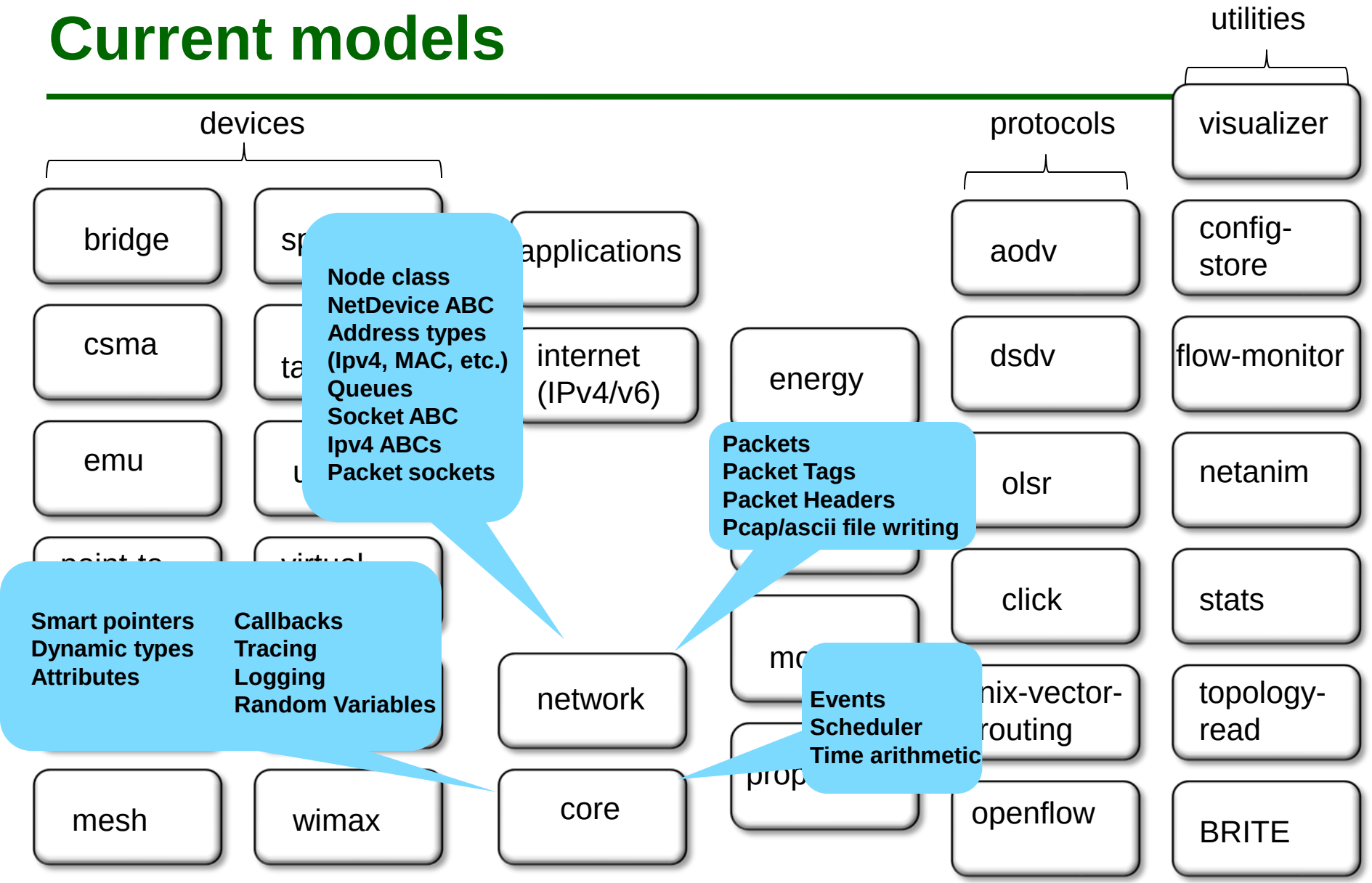


2) ns-3 modules exist within the ns-3 directory

Current models



Current models



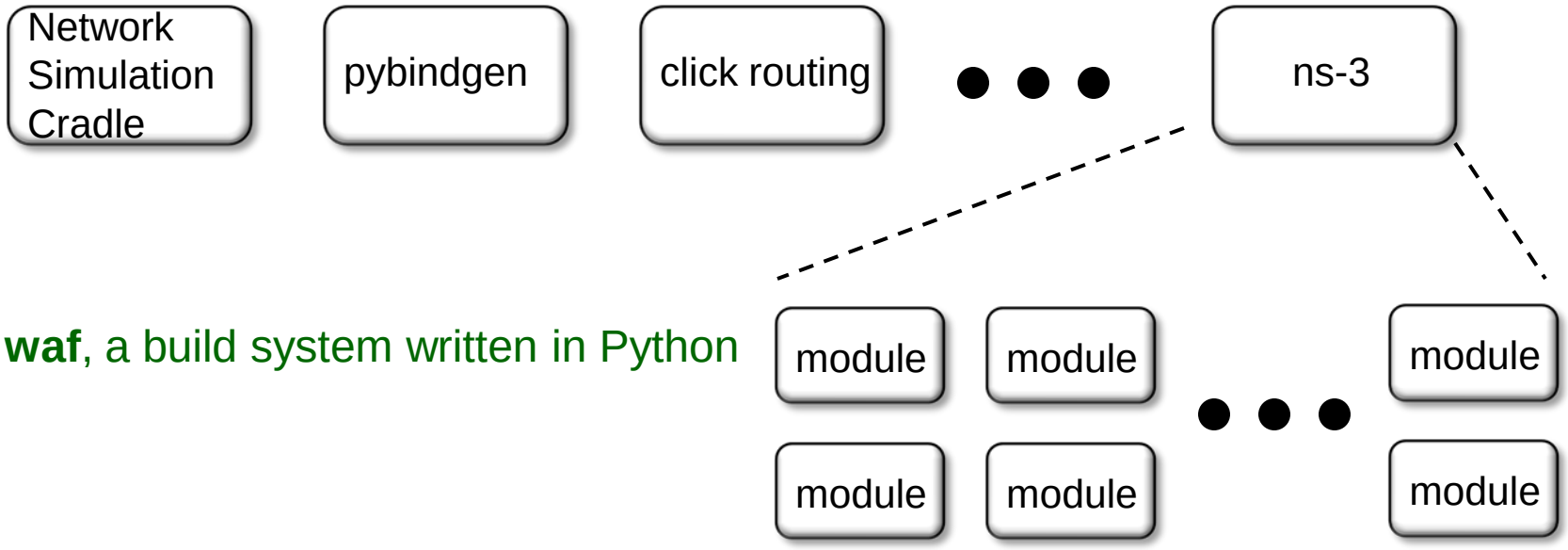
Module organization

- models/
- examples/
- tests/
- bindings/
- doc/
- wscript

Software building

- Two levels of ns-3 build

1) build.py (a custom Python build script to control an ordered build of ns-3 and its libraries)



2) waf, a build system written in Python

ns-3 uses the 'waf' build system

- Waf is a Python-based framework for configuring, compiling and installing applications.
  - It is a replacement for other tools such as Autotools, Scons, CMake or Ant
  - http://code.google.com/p/waf/
- For those familiar with autotools:
- `configure` → `./waf configure`
- `make` → `./waf build`

waf configuration

- Key waf configuration examples

```
./waf configure
    --enable-examples
    --enable-tests
    --disable-python
    --enable-modules
```

- Whenever build scripts change, need to reconfigure

Demo: `./waf --help`
`./waf configure --enable-examples --enable-tests --enable-modules='core'`
Look at: `build/c4che/_cache.py`

wscript example

```
## -*- Mode: python; py-indent-offset: 4; indent-tabs-mode: nil; coding: utf-8; -*-

def build(bld):
    obj = bld.create_ns3_module('csma', ['network', 'applications'])
    obj.source = [
        'model/backoff.cc',
        'model/csma-net-device.cc',
        'model/csma-channel.cc',
        'helper/csma-helper.cc',
        ]
    headers = bld.new_task_gen(features=['ns3header'])
    headers.module = 'csma'
    headers.source = [
        'model/backoff.h',
        'model/csma-net-device.h',
        'model/csma-channel.h',
        'helper/csma-helper.h',
        ]

    if bld.env['ENABLE_EXAMPLES']:
        bld.add_subdirs('examples')

    bld.ns3_python_bindings()
```

waf build

- Once project is configured, can build via `./waf build` or `./waf`
- waf will build in parallel on multiple cores
- waf displays modules built at end of build

Demo: `./waf build`

Look at: `build/` libraries and executables

Running programs

- `./waf shell` provides a special shell for running programs
  - Sets key environment variables

```
./waf --run sample-simulator
./waf --pyrun src/core/examples/sample-simulator.py
```

Discrete-event simulation basics

- Simulation time moves in discrete jumps from event to event
- C++ functions schedule events to occur at specific simulation times
- A simulation scheduler orders the event execution
- Simulation::Run() gets it all started
- Simulation stops at specific time or when events end

Simulator example

```
#include <iostream>
#include "ns3/simulator.h"
#include "ns3/nstime.h"
#include "ns3/command-line.h"
#include "ns3/double.h"
#include "ns3/random-variable-stream.h"

using namespace ns3;
```

```
int main (int argc, char *argv[])
{
  CommandLine cmd;
  cmd.Parse (argc, argv);

  MyModel model;
  Ptr<UniformRandomVariable> v = CreateObject<UniformRandomVariable> ();
  v->SetAttribute ("Min", DoubleValue (10));
  v->SetAttribute ("Max", DoubleValue (20));

  Simulator::Schedule (Seconds (10.0), &ExampleFunction, &model);

  Simulator::Schedule (Seconds (v->GetValue ()), &RandomFunction);

  EventId id = Simulator::Schedule (Seconds (30.0), &CancelledEvent);
  Simulator::Cancel (id);

  Simulator::Run ();

  Simulator::Destroy ();
}
```

Simulator example (in Python)

```
# Python version of sample-simulator.cc

import ns.core
```

```
def main(dummy_argv):

    model = MyModel()
    v = ns.core.UniformRandomVariable()
    v.SetAttribute("Min", ns.core.DoubleValue (10))
    v.SetAttribute("Max", ns.core.DoubleValue (20))

    ns.core.Simulator.Schedule(ns.core.Seconds(10.0), ExampleFunction, model)

    ns.core.Simulator.Schedule(ns.core.Seconds(v.GetValue()), RandomFunction, model)

    id = ns.core.Simulator.Schedule(ns.core.Seconds(30.0), CancelledEvent)
    ns.core.Simulator.Cancel(id)

    ns.core.Simulator.Run()

    ns.core.Simulator.Destroy()

if __name__ == '__main__':
    import sys
    main(sys.argv)
```

Command-line arguments

- Add CommandLine to your program if you want command-line argument parsing

```
int main (int argc, char *argv[])
{
  CommandLine cmd;
  cmd.Parse (argc, argv);
```

- Passing --PrintHelp to programs will display command line options, if CommandLine is enabled

```
./waf --run "sample-simulator --PrintHelp"
```

```
--PrintHelp: Print this help message.
--PrintGroups: Print the list of groups.
--PrintTypeIds: Print all TypeIds.
--PrintGroup=[group]: Print all TypeIds of group.
--PrintAttributes=[typeid]: Print all attributes of typeid.
--PrintGlobals: Print the list of globals.
```

Time in ns-3

- Time is stored as a large integer in ns-3
  - Avoid floating point discrepancies across platforms
- Special Time classes are provided to manipulate time (such as standard operators)
- Default time resolution is nanoseconds, but can be set to other resolutions
- Time objects can be set by floating-point values and can export floating-point

```
double timeDouble = t.GetSeconds();
```

Events in ns-3

- Events are just function calls that execute at a simulated time
  - i.e. callbacks
- Events have IDs to allow them to be cancelled or to test their status

Simulator and Schedulers

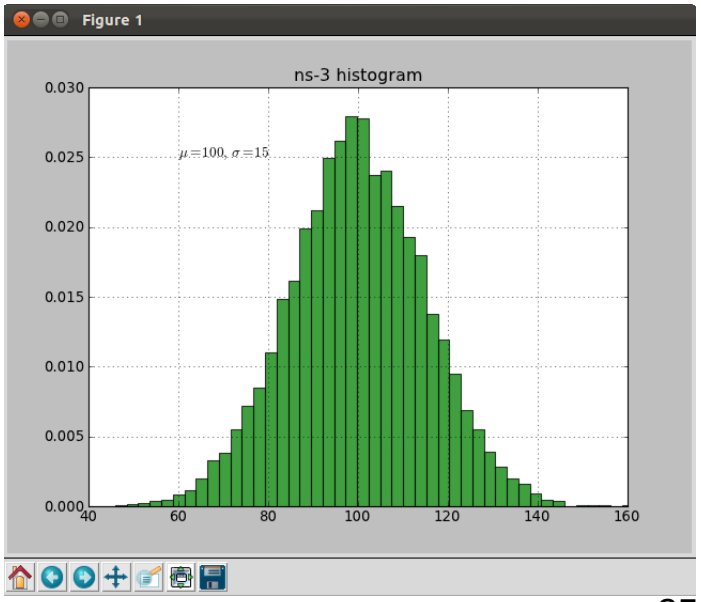
- The Simulator class holds a scheduler, and provides the API to schedule events, start, stop, and cleanup memory
- Several scheduler data structures (calendar, heap, list, map) are possible
- A "RealTime" simulation implementation is possible
  - aligns the simulation time to wall-clock time

Random Variables

from src/core/examples/sample-rng-plot.py

- Currently implemented distributions
  - Uniform: values uniformly distributed in an interval
  - Constant: value is always the same (not really random)
  - Sequential: return a sequential list of predefined values
  - Exponential: exponential distribution (poisson process)
  - Normal (gaussian), Log-Normal, Pareto, Weibull, triangular

```
# Demonstrate use of ns-3 as a random number generator integrated with
# plotting tools; adapted from Gustavo Carneiro's ns-3 tutorial

import numpy as np
import matplotlib.pyplot as plt
import ns.core

# mu, var = 100, 225
rng = ns.core.NormalVariable(100.0, 225.0)
x = [rng.GetValue() for t in range(10000)]

# the histogram of the data
n, bins, patches = plt.hist(x, 50, normed=1, facecolor='g', alpha=0.75)

plt.title('ns-3 histogram')
plt.text(60, .025, r'$\mu=100,\ \sigma=15$')
plt.axis([40, 160, 0, 0.03])
plt.grid(True)
plt.show()
```



Random variables and independent replications

- Many simulation uses involve running a number of *independent replications* of the same scenario

- In ns-3, this is typically performed by incrementing the simulation *run number*
  - *not by changing seeds*

ns-3 random number generator

- Uses the MRG32k3a generator from Pierre L'Ecuyer
  - http://www.iro.umontreal.ca/~lecuyer/myftp/papers/streams00.pdf
  - Period of PRNG is 3.1x10^57
- Partitions a pseudo-random number generator into uncorrelated *streams* and *substreams*
  - Each RandomVariableStream gets its own stream
  - This stream partitioned into substreams

Run number vs. seed

- If you increment the seed of the PRNG, the streams of random variable objects across different runs are not guaranteed to be uncorrelated
- If you fix the seed, but increment the run number, you will get an uncorrelated substream

Putting it together

- Example of scheduled event

```
static void
RandomFunction (void)
{
  std::cout << "RandomFunction received event at "
            << Simulator::Now ().GetSeconds () << "s" << std::endl;
}
```

```
int main (int argc, char *argv[])
{
  CommandLine cmd;
  cmd.Parse (argc, argv);

  MyModel model;
  Ptr<UniformRandomVariable> v = CreateObject<UniformRandomVariable> ();
  v->SetAttribute ("Min", DoubleValue (10));
  v->SetAttribute ("Max", DoubleValue (20));

  Simulator::Schedule (Seconds (10.0), &ExampleFunction, &model);

  Simulator::Schedule (Seconds (v->GetValue ()), &RandomFunction);
```

Demo real-time, command-line, random variables...

Build variations

- Configure a build type is done at waf configuration time
- debug build (default): all asserts and debugging code enabled

```
./waf -d debug configure
```

- optimized

```
./waf -d optimized configure
```

- static libraries

```
./waf --enable-static configure
```

Controlling the modular build

- One way to disable modules:
  - `./waf configure --enable-modules='a','b','c'`
- The `.ns3rc` file (found in utils/ directory) can be used to control the modules built
- Precedence in controlling build

  1) command line arguments

  2) .ns3rc in ns-3 top level directory

  3) .ns3rc in user's home directory

Demo how .ns3rc works

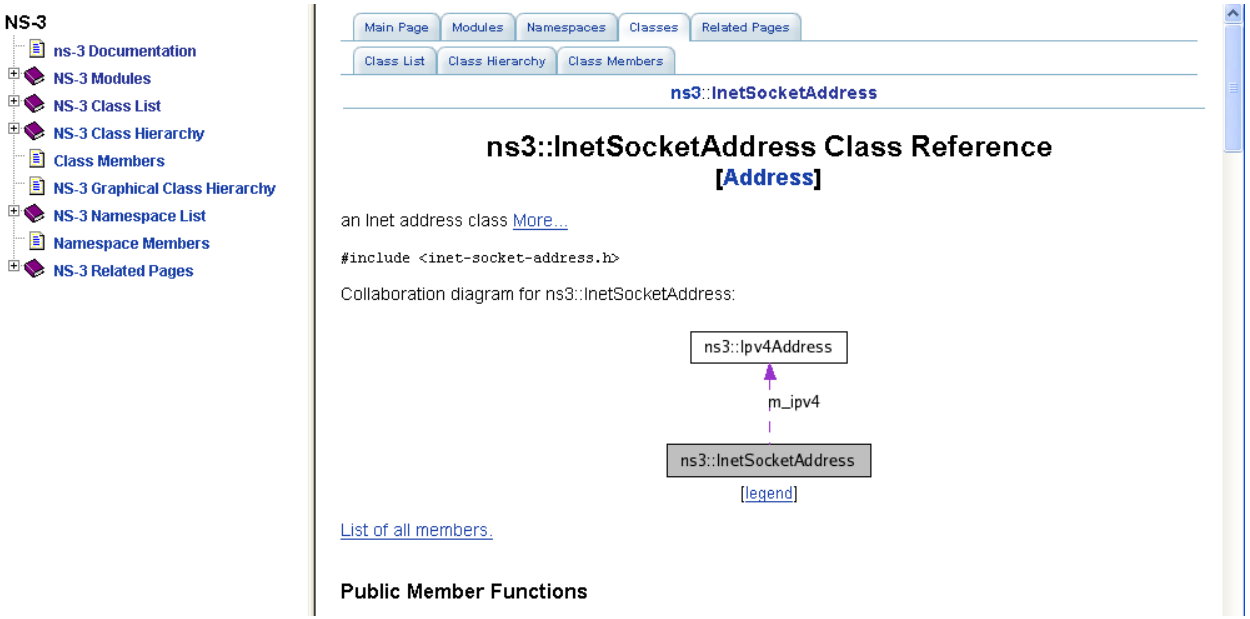
Building without wscript

- The scratch/ directory can be used to build programs without wscripts

Demo how programs can be built without wscripts

APIs

- Most of the ns-3 API is documented with Doxygen
  - http://www.stack.nl/~dimitri/doxygen/

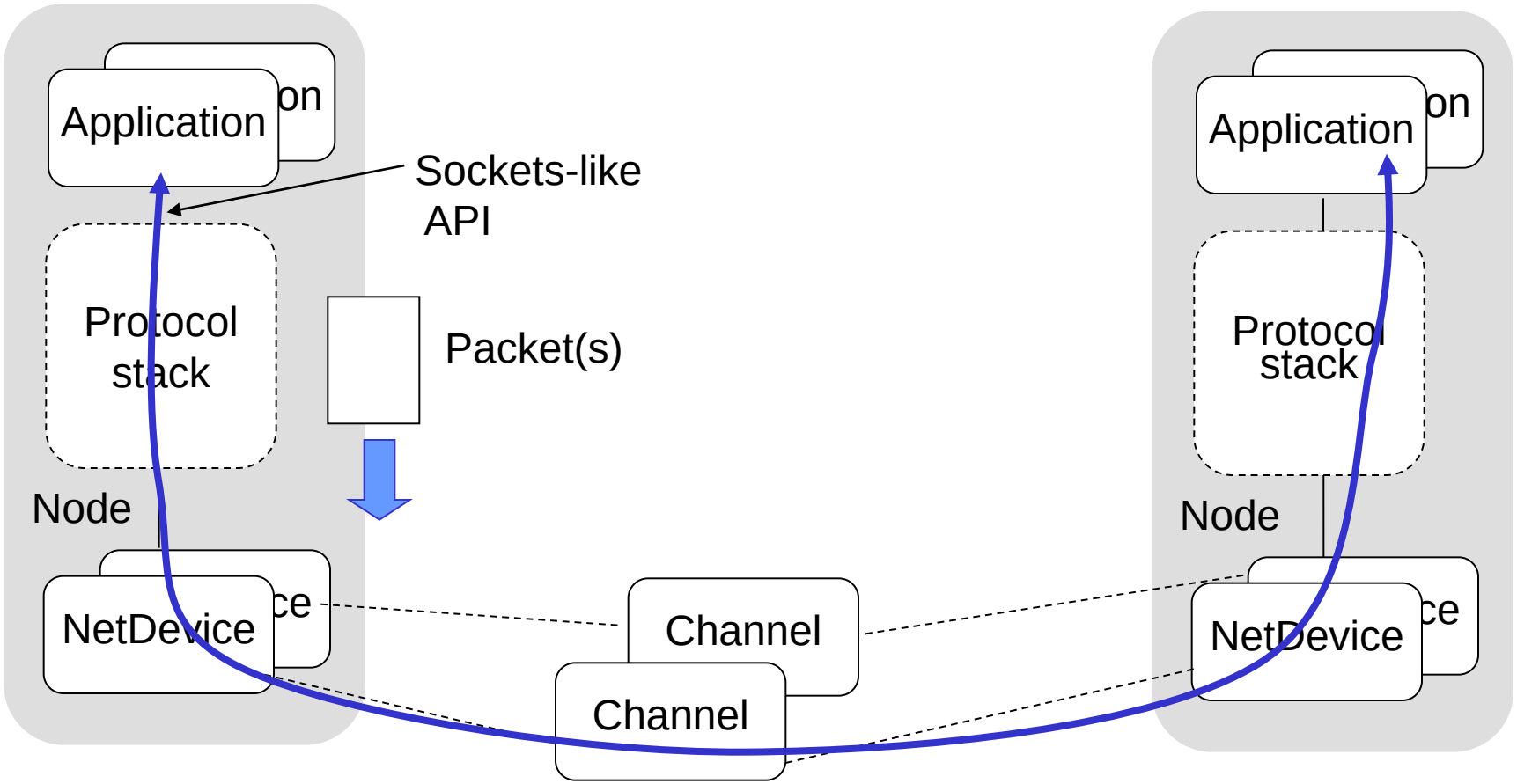


Review of topics covered

- Software layout
- Software build
- Library documentation
- Basic discrete-event simulation concepts
- Control of randomness
- Simulation time
- A simple C++ ns-3 program
- A simple Python ns-3 program

Walkthrough of WiFi Internet example

The basic model

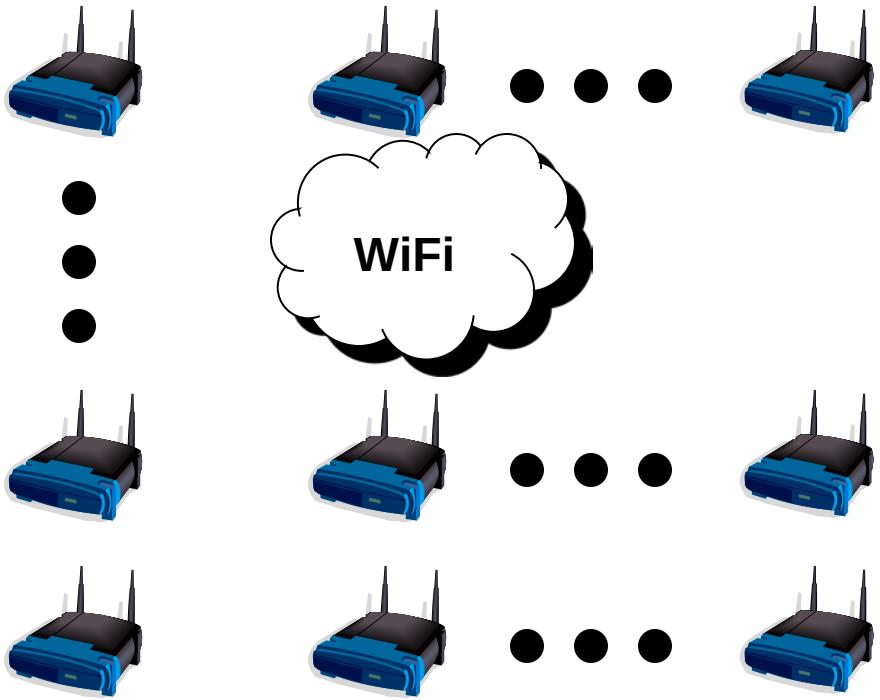


Example program

- `examples/wireless/wifi-simple-adhoc-grid.cc`
- examine wscript for necessary modules
  - `'internet', 'mobility', 'wifi', 'config-store', 'tools'`
  - we'll add `'visualizer'`
- `./waf configure --enable-examples --enable-modules=...`

Example program

- (5x5) grid of WiFi ad hoc nodes
- OLSR packet routing
- Try to send packet from one node to another



Source (node 24) by default

Sink (node 0) by default

- Goal is to read and understand the high-level ns-3 API

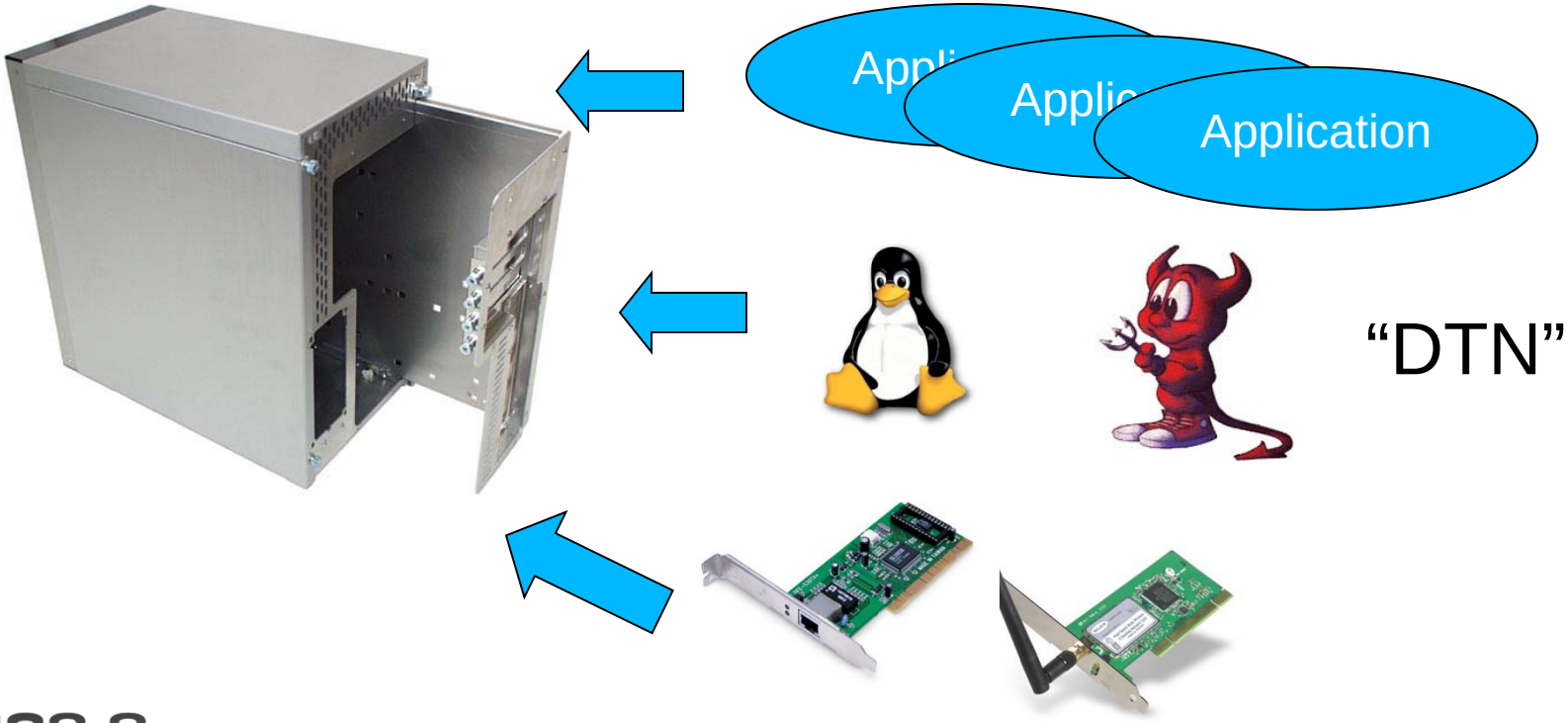
Fundamentals

Key objects in the simulator are Nodes, Packets, and Channels

Nodes contain Applications, “stacks”, and NetDevices

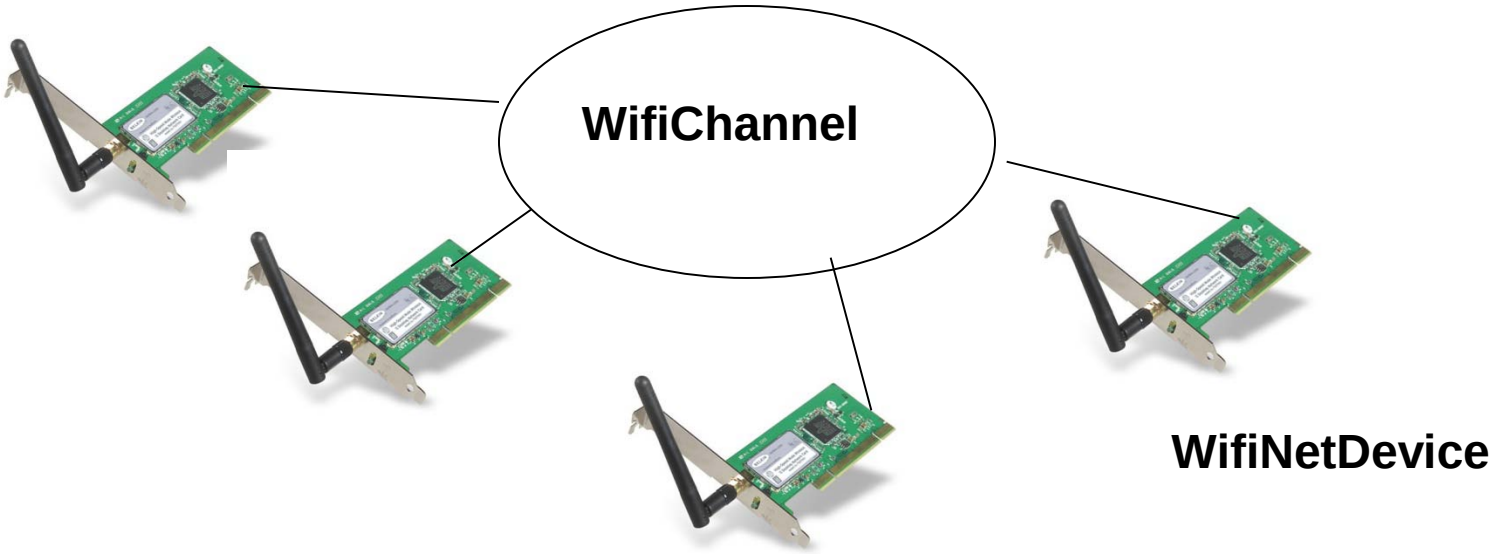
Node basics

A Node is a shell of a computer to which applications, stacks, and NICs are added



NetDevices and Channels

NetDevices are strongly bound to Channels of a matching type



Nodes are architected for multiple interfaces

Internet Stack

- Internet Stack
  - Provides IPv4 and some IPv6 models currently
- No non-IP stacks presently in ns-3
  - but no dependency on IP in the devices, Node, Packet, etc.
  - some activity on IEEE 802.15.4-based models

Other basic models in ns-3

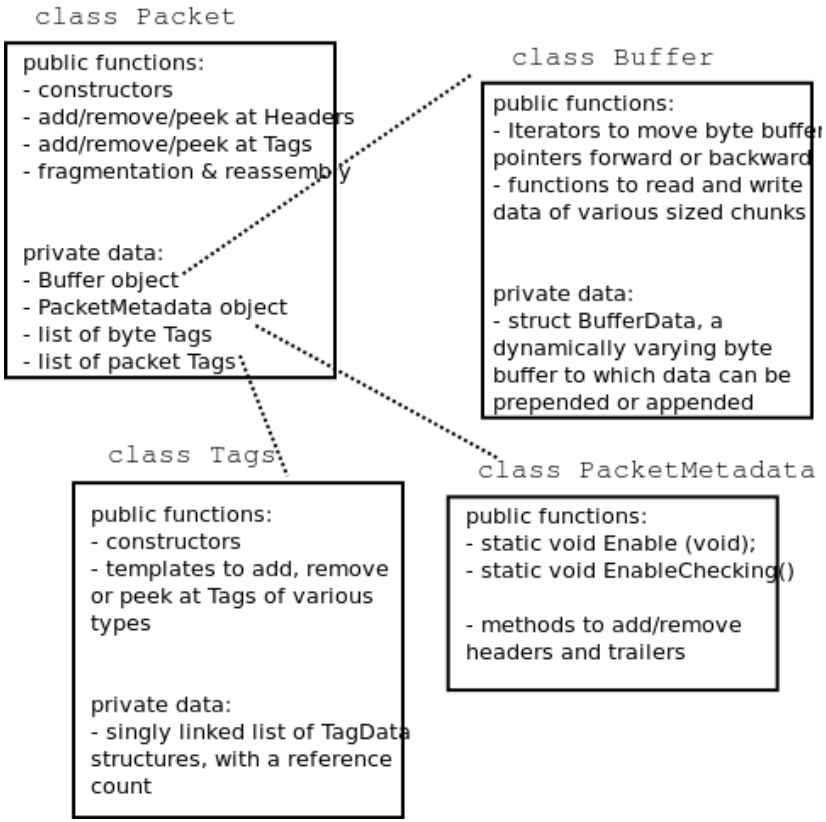
- Devices
  - WiFi, WiMAX, CSMA, Point-to-point, Bridge
- Error models and queues
- Applications
  - echo servers, traffic generator
- Mobility models
- Packet routing
  - OLSR, AODV, DSR, DSDV, Static, Nix-Vector, Global (link state)

ns-3 Packet

- Packet is an advanced data structure with the following capabilities
  - Supports fragmentation and reassembly
  - Supports real or virtual application data
  - Extensible
  - Serializable (for emulation)
  - Supports pretty-printing
  - Efficient (copy-on-write semantics)

ns-3 Packet structure

- Analogous to an mbuf/skbuff



Copy-on-write

- Copy data bytes only as needed

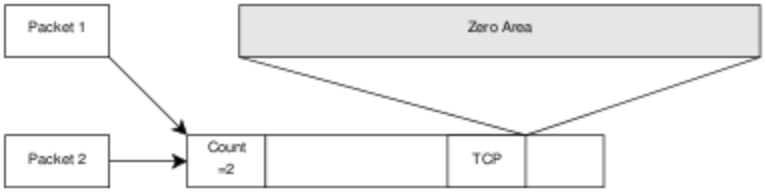


Figure 3.8: The TCP and the IP stacks hold references to a shared buffer.

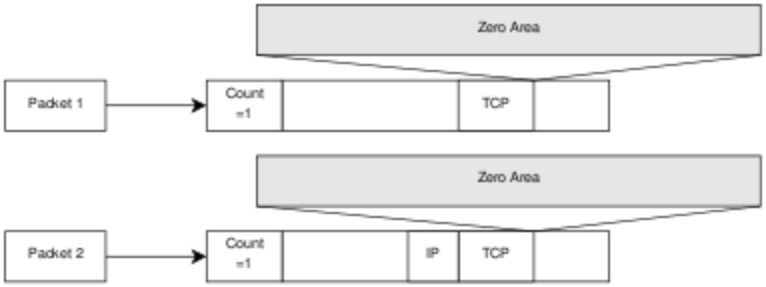


Figure 3.9: The IP stack inserts the IP header, triggers an un-share operation, completes the insertion.

Structure of an ns-3 program

```
int main (int argc, char *argv[])
{

  // Set default attribute values

  // Parse command-line arguments

  // Configure the topology; nodes, channels, devices, mobility

  // Add (Internet) stack to nodes

  // Configure IP addressing and routing

  // Add and configure applications

  // Configure tracing

  // Run simulation
}
```

Review of example program

```
NodeContainer c;
c.Create (numNodes);

// The below set of helpers will help us to put together the wifi NICs we want
WifiHelper wifi;
if (verbose)
  {
    wifi.EnableLogComponents ();  // Turn on all Wifi logging
  }

YansWifiPhyHelper wifiPhy =  YansWifiPhyHelper::Default ();
// set it to zero; otherwise, gain will be added
wifiPhy.Set ("RxGain", DoubleValue (-10) );
// ns-3 supports RadioTap and Prism tracing extensions for 802.11b
wifiPhy.SetPcapDataLinkType (YansWifiPhyHelper::DLT_IEEE802_11_RADIO);

YansWifiChannelHelper wifiChannel;
wifiChannel.SetPropagationDelay ("ns3::ConstantSpeedPropagationDelayModel");
wifiChannel.AddPropagationLoss ("ns3::FriisPropagationLossModel");
wifiPhy.SetChannel (wifiChannel.Create ());

// Add a non-QoS upper mac, and disable rate control
NqosWifiMacHelper wifiMac = NqosWifiMacHelper::Default ();
wifi.SetStandard (WIFI_PHY_STANDARD_80211b);
wifi.SetRemoteStationManager ("ns3::ConstantRateWifiManager",
                              "DataMode",StringValue (phyMode),
                              "ControlMode",StringValue (phyMode));
// Set it to adhoc mode
wifiMac.SetType ("ns3::AdhocWifiMac");
NetDeviceContainer devices = wifi.Install (wifiPhy, wifiMac, c);

MobilityHelper mobility;
```

Helper API

- The ns-3 “helper API” provides a set of classes and methods that make common operations easier than using the low-level API
- Consists of:
  - container objects
  - helper classes
- The helper API is implemented using the low-level API
- Users are encouraged to contribute or propose improvements to the ns-3 helper API

Containers

- Containers are part of the ns-3 “helper API”
- Containers group similar objects, for convenience
  - They are often implemented using C++ std containers
- Container objects also are intended to provide more basic (typical) API

The Helper API (vs. low-level API)

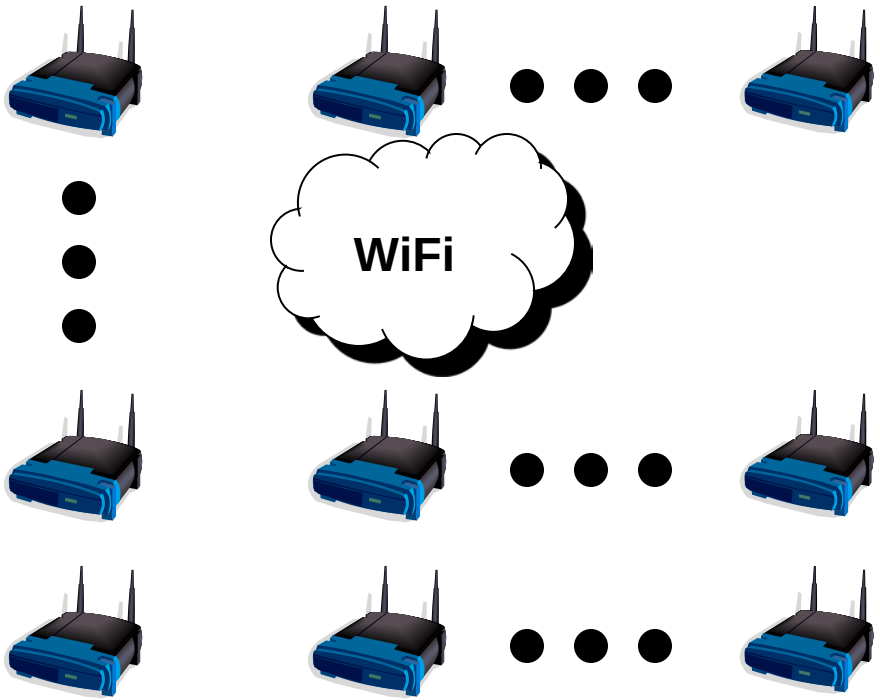
- Is not generic
- Does not try to allow code reuse
- Provides simple 'syntactical sugar' to make simulation scripts look nicer and easier to read for network researchers
- Each function applies a single operation on a "set of same objects”

Helper Objects

- NodeContainer: vector of Ptr<Node>
- NetDeviceContainer: vector of Ptr<NetDevice>
- InternetStackHelper
- WifiHelper
- MobilityHelper
- OlsrHelper
- ... Each model provides a helper class

Example program

- (5x5) grid of WiFi ad hoc nodes
- OLSR packet routing
- Try to send packet from one node to another



Source (node 24) by default

Sink (node 0) by default

- Let's look closely at how these objects are created

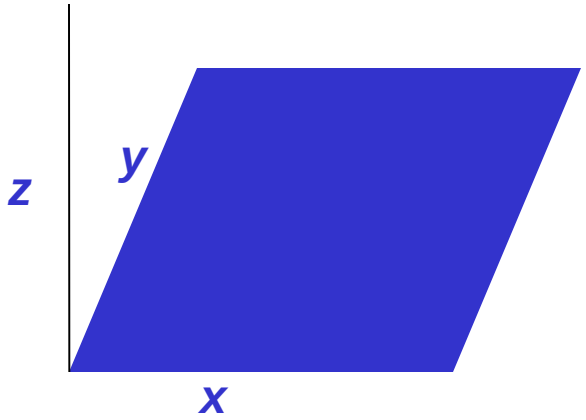
Installation onto containers

- Installing models into containers, and handling containers, is a key API theme

```
NodeContainer c;
c.Create (numNodes);
...
mobility.Install (c);
...
internet.Install (c);
...
```

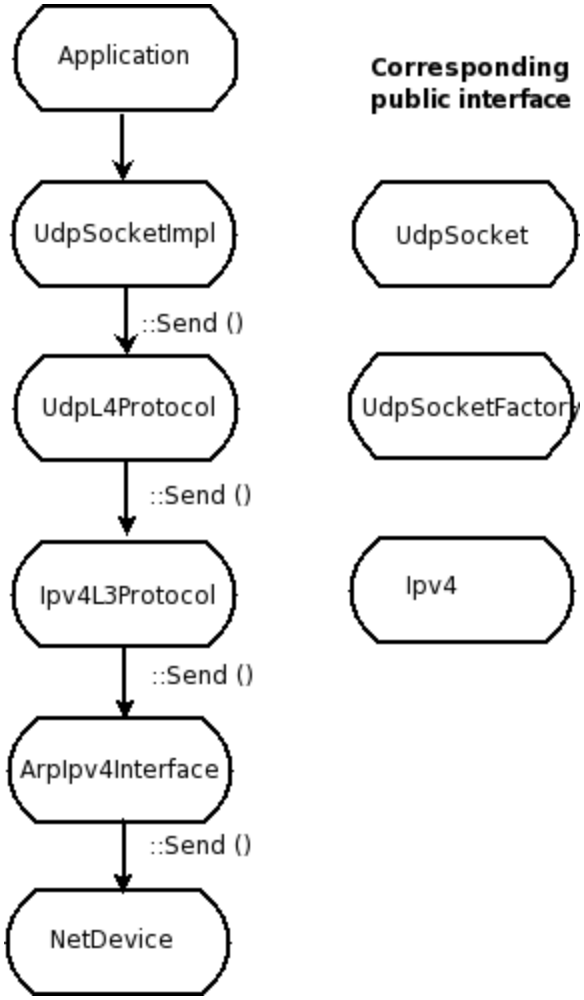
Mobility models in ns-3

- The MobilityModel interface:
  - void SetPosition (Vector pos)
  - Vector GetPosition ()
- StaticMobilityModel
  - Node is at a fixed location; does not move on its own
- RandomWaypointMobilityModel
  - (works inside a rectangular bounded area)
  - Node pauses for a certain random time
  - Node selects a random waypoint and speed
  - Node starts walking towards the waypoint
  - When waypoint is reached, goto first state
- RandomDirectionMobilityModel
  - works inside a rectangular bounded area)
  - Node selects a random direction and speed
  - Node walks in that direction until the edge
  - Node pauses for random time
  - Repeat



3D Cartesian coordinate system

Internet stack



- The public interface of the Internet stack is defined (abstract base classes) in src/network/model directory
- The intent is to support multiple implementations
- The default ns-3 Internet stack is implemented in src/internet-stack

ns-3 TCP

- Several options exist:
  - native ns-3 TCP
    - Tahoe, Reno, NewReno (others in development)
  - TCP simulation cradle (NSC)
  - Use of virtual machines or DCE (more on this later)

- To enable NSC:

```
internetStack.SetNscStack ("liblinux2.6.26.so");
```

ns-3 simulation cradle

- Port by Florian Westphal of Sam Jansen's Ph.D. work

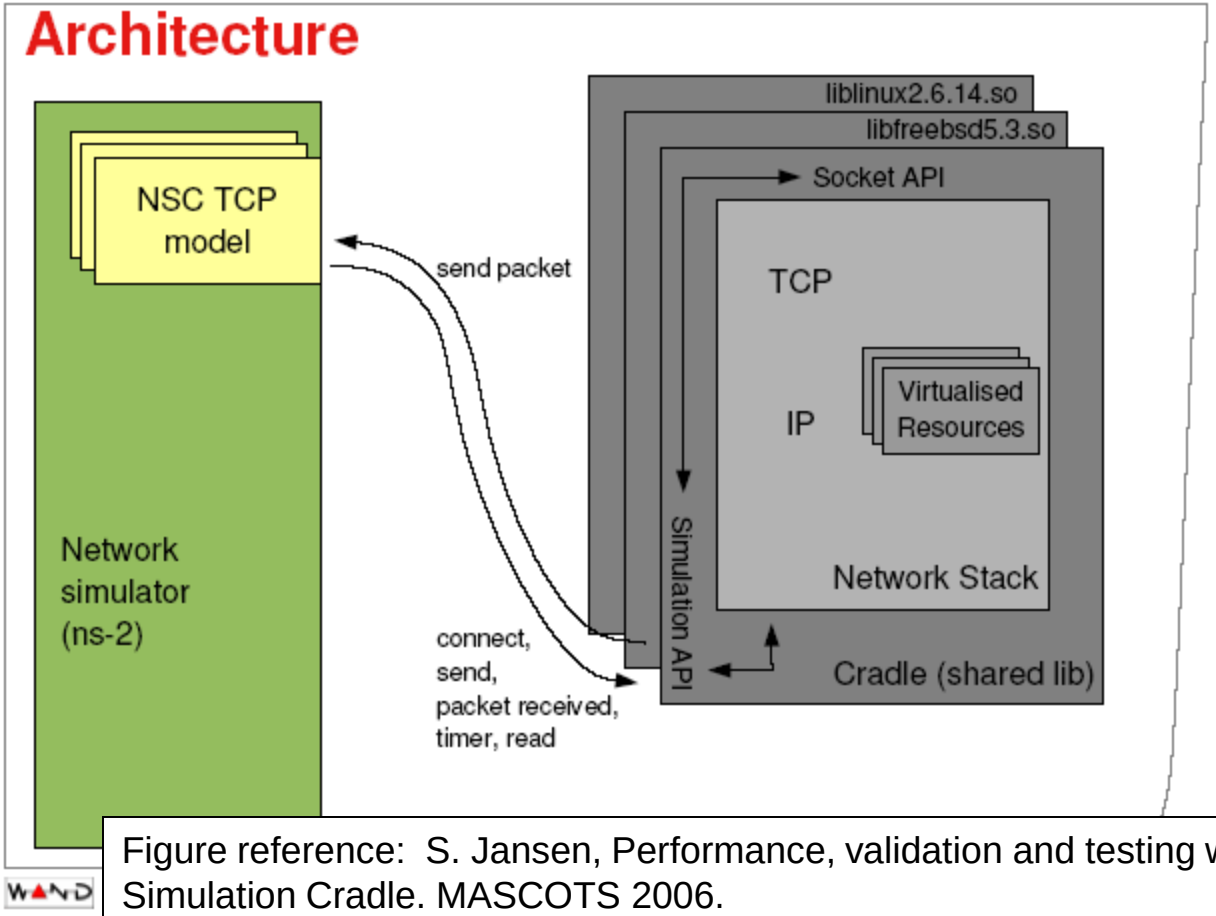
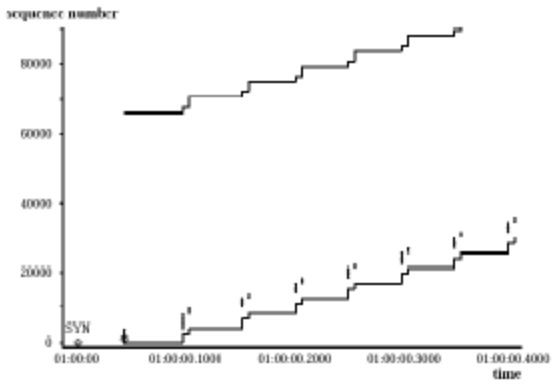


Figure reference: S. Jansen, Performance, validation and testing with the Network Simulation Cradle. MASCOTS 2006.

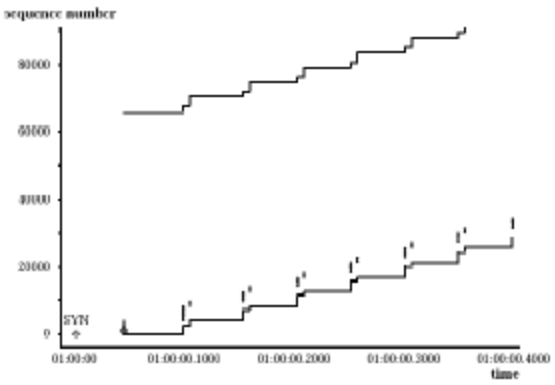
ns-3 simulation cradle

Accuracy

•Have shown NSC to be very accurate – able to produce packet traces that are almost identical to traces measured from a test network



(a) Simulated FreeBSD



(b) Measured FreeBSD

Figure reference: S. Jansen, Performance, validation and testing with the Network Simulation Cradle. MASCOTS 2006.

For ns-3:
- Linux 2.6.18
- Linux 2.6.26
- Linux 2.6.28

Others:
- FreeBSD 5
- lwip 1.3
- OpenBSD 3

Other simulators:
- ns-2
- OmNET++

IPv4 address configuration

- An Ipv4 address helper can assign addresses to devices in a NetDevice container

```
Ipv4AddressHelper ipv4;
ipv4.SetBase ("10.1.1.0", "255.255.255.0");
csmaInterfaces = ipv4.Assign (csmaDevices);

...

ipv4.NewNetwork ();  // bumps network to 10.1.2.0
otherCsmaInterfaces = ipv4.Assign (otherCsmaDevices);
```

Applications and sockets

- In general, applications in ns-3 derive from the ns3::Application base class
  - A list of applications is stored in the ns3::Node
  - Applications are like processes
- Applications make use of a sockets-like API
  - Application::Start () may call ns3::Socket::SendMsg() at a lower layer

Sockets API

Plain C sockets

```
int sk;
sk = socket(PF_INET, SOCK_DGRAM, 0);
```

```
struct sockaddr_in src;
inet_pton(AF_INET,"0.0.0.0",&src.sin_ad
   dr);
src.sin_port = htons(80);
bind(sk, (struct sockaddr *) &src,
   sizeof(src));
```

```
struct sockaddr_in dest;
inet_pton(AF_INET,"10.0.0.1",&dest.sin_
   addr);
dest.sin_port = htons(80);
sendto(sk, "hello", 6, 0, (struct
   sockaddr *) &dest, sizeof(dest));
```

```
char buf[6];
recv(sk, buf, 6, 0);
}
```

ns-3 sockets

```
Ptr<Socket> sk =
udpFactory->CreateSocket ();
```

```
sk->Bind (InetSocketAddress (80));
```

```
sk->SendTo (InetSocketAddress (Ipv4Address
   ("10.0.0.1"), 80), Create<Packet>
   ("hello", 6));
```

```
sk->SetReceiveCallback (MakeCallback
   (MySocketReceive));
```

- […] (Simulator::Run ())

```
void MySocketReceive (Ptr<Socket> sk,
   Ptr<Packet> packet)
{
...
}
```

ns-3 tutorial agenda

- 13h00-15h00: Getting started with ns-3
  - Overview of software and models
  - Basic structure of the core and important models
  -
- 15h00-15h30: 30-minute coffee break
- 15h40-17h15: Going further with ns-3
  - Running and understanding an existing example
  - Animation and visualization
  - Writing and debugging your own examples
  - Integrating other tools and libraries
  - Parallel simulations
  - Emulation, virtual machine and testbed integration
  - Getting help and getting involved

Attributes and default values

```
// disable fragmentation for frames below 2200 bytes
Config::SetDefault ("ns3::WifiRemoteStationManager::FragmentationThreshold", StringValue ("22
00"));
// turn off RTS/CTS for frames below 2200 bytes
Config::SetDefault ("ns3::WifiRemoteStationManager::RtsCtsThreshold", StringValue ("2200"));
// Fix non-unicast data rate to be the same as that of unicast
Config::SetDefault ("ns3::WifiRemoteStationManager::NonUnicastMode",
                    StringValue (phyMode));

NodeContainer c;
c.Create (numNodes);

// The below set of helpers will help us to put together the wifi NICs we want
WifiHelper wifi;
if (verbose)
  {
    wifi.EnableLogComponents ();  // Turn on all Wifi logging
  }

YansWifiPhyHelper wifiPhy =  YansWifiPhyHelper::Default ();
// set it to zero; otherwise, gain will be added
wifiPhy.Set ("RxGain", DoubleValue (-10) );
// ns-3 supports RadioTap and Prism tracing extensions for 802.11b
wifiPhy.SetPcapDataLinkType (YansWifiPhyHelper::DLT_IEEE802_11_RADIO);
```

ns-3 attribute system

Problem: Researchers want to identify all of the values affecting the results of their simulations

- and configure them easily

ns-3 solution: Each ns-3 object has a set of attributes:

- A name, help text
- A type
- An initial value

- Control all simulation parameters for static objects
- Dump and read them all in configuration files
- Visualize them in a GUI
- Makes it easy to verify the parameters of a simulation

Short digression: Object metadata system

- ns-3 is, at heart, a C++ object system
- ns-3 objects that inherit from base class ns3::Object get several additional features
  - dynamic run-time object aggregation
  - an attribute system 
  - smart-pointer memory management (Class Ptr)

We focus here on the attribute system

Use cases for attributes

- An Attribute represents a value in our system
- An Attribute can be connected to an underlying variable or function
  - e.g. TcpSocket::m_cwnd;
  - or a trace source

Use cases for attributes (cont.)

- What would users like to do?
  - Know what are all the attributes that affect the simulation at run time
  - Set a default initial value for a variable
  - Set or get the current value of a variable
  - Initialize the value of a variable when a constructor is called
- The attribute system is a unified way of handling these functions

How to handle attributes

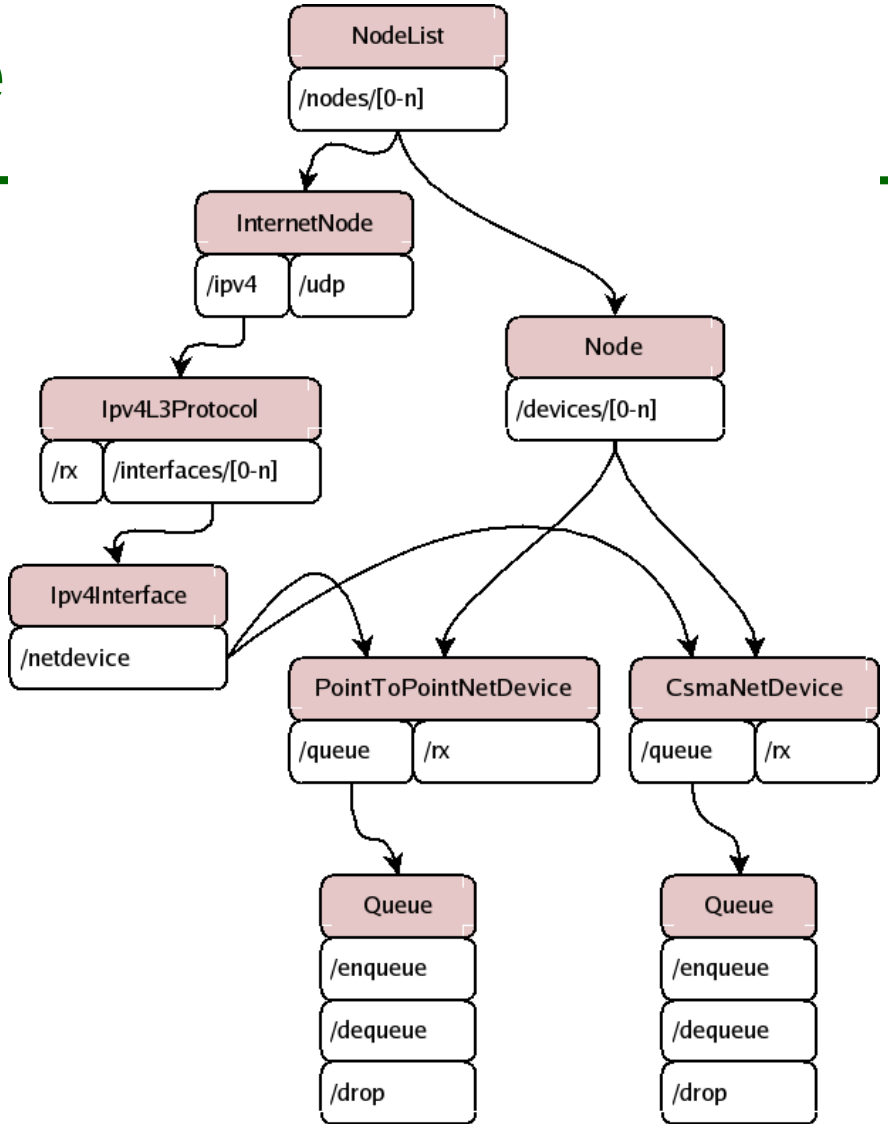
- The traditional C++ way:
  - export attributes as part of a class's public API
  - walk pointer chains (and iterators, when needed) to find what you need
  - use static variables for defaults
- The attribute system provides a more convenient API to the user to do these things

Navigating the attributes

- Attributes are exported into a string-based namespace, with filesystem-like paths
  - namespace supports regular expressions
- Attributes also can be used without the paths
  - e.g. “`ns3::WifiPhy::TxGain`”
- A Config class allows users to manipulate the attributes

Attribute namespace

- strings are used to describe paths through the namespace




```
Config::Set ("/NodeList/1/$ns3::Ns3NscStack<linux2.6.26>/net.ipv4.tcp_sack", StringValue ("0"));
```

Navigating the attributes using paths

- Examples:
  - Nodes with NodeIds 1, 3, 4, 5, 8, 9, 10, 11:

    `"/NodeList/[3-5]|[8-11]|1"`
  - UdpL4Protocol object instance aggregated to matching nodes:

    `"/$ns3::UdpL4Protocol"`

What users will do

- e.g.: Set a default initial value for a variable

```
Config::Set (“ns3::WifiPhy::TxGain”,
  DoubleValue (1.0));
```

- Syntax also supports string values:

```
Config::Set (“WifiPhy::TxGain”, StringValue
  (“1.0”));
```

Fine-grained attribute handling

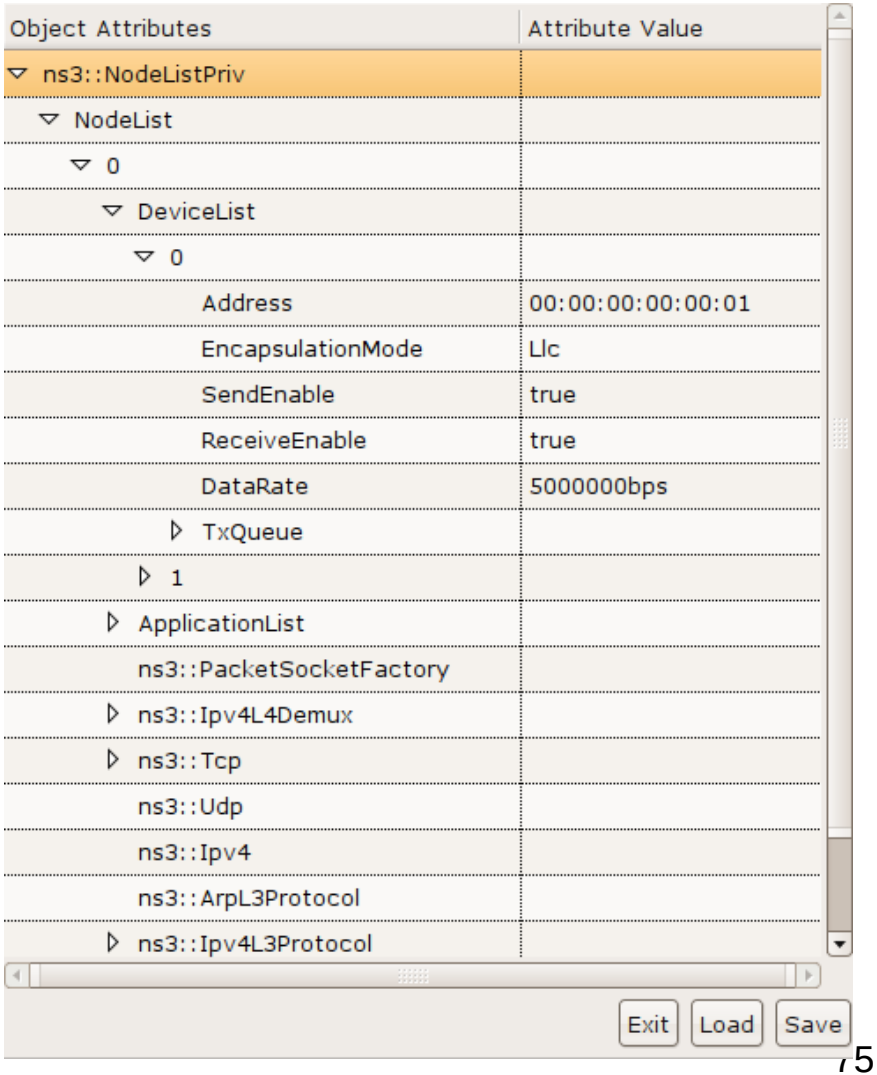
- Set or get the current value of a variable
  - Here, one needs the path in the namespace to the right instance of the object

```
Config::SetAttribute("/NodeList/5/DeviceList/3/Phy/TxGain", DoubleValue(1.0));
DoubleValue d; nodePtr->GetAttribute ( "/NodeList/5/NetDevice/3/Phy/TxGain", v);
```

- Users can get Ptrs to instances also, and Ptrs to trace sources, in the same way

ns-3 attribute system

- Object attributes are organized and documented in the Doxygen
- Enables the construction of graphical configuration tools:



Attribute documentation

Main Page | Related Pages | Modules | Namespaces | Classes | Files

The list of all attributes.

[Core]

Collaboration diagram for The list of all attributes.:

ns3::V4Ping

- Remote: The address of the machine we want to ping.

ns3::ConstantRateWifiManager

- DataMode: The transmission mode to use for every data packet transmission
- ControlMode: The transmission mode to use for every control packet transmission.

ns3::WifiRemoteStationManager

- IsLowLatency: If true, we attempt to modelize a so-called low-latency device: a device where decisions about tx parameters can be made on a per-packet basis and feedback about the transmission of each packet is obtained before sending the next. Otherwise, we modelize a high-latency device, that is a device where we cannot update our decision about tx parameters after every packet transmission.
- MaxSsrc: The maximum number of retransmission attempts for an RTS. This value will not have any effect on some rate control algorithms.
- MaxSlrc: The maximum number of retransmission attempts for a DATA packet. This value will not have any effect on some rate control algorithms.
- RtsCtsThreshold: If a data packet is bigger than this value, we use an RTS/CTS handshake before sending the data. This value will not have any effect on some rate control algorithms.

Options to manipulate attributes

- Individual object attributes often derive from default values
  - Setting the default value will affect all subsequently created objects
  - Ability to configure attributes on a per-object basis
- Set the default value of an attribute from the command-line:

```
CommandLine cmd;
cmd.Parse (argc, argv);
```

- Set the default value of an attribute with NS_ATTRIBUTE_DEFAULT
- Set the default value of an attribute in C++:

```
Config::SetDefault ("ns3::Ipv4L3Protocol::CalcChecksum",
BooleanValue (true));
```

- Set an attribute directly on a specic object:

```
Ptr<CsmaChannel> csmaChannel = ...;
csmaChannel->SetAttribute ("DataRate",
StringValue ("5Mbps"));
```

Object names

- It can be helpful to refer to objects by a string name
  - "access point"
  - "eth0"
- Objects can now be associated with a name, and the name used in the attribute system

Names example

```
NodeContainer n;
n.Create (4);
Names::Add ("client", n.Get (0));
Names::Add ("server", n.Get (1));
...

Names::Add ("client/eth0", d.Get (0));
...

Config::Set ("/Names/client/eth0/Mtu", UintegerValue
  (1234));
```

Equivalent to:

```
Config::Set (“/NodeList/0/DeviceList/0/Mtu”, UintegerValue
  (1234));
```

Tracing and statistics

- Tracing is a structured form of simulation output
- Example (from ns-2):

```
+ 1.84375 0 2 cbr 210 ------- 0 0.0 3.1 225 610
- 1.84375 0 2 cbr 210 ------- 0 0.0 3.1 225 610
r 1.84471 2 1 cbr 210 ------- 1 3.0 1.0 195 600
r 1.84566 2 0 ack 40 ------- 2 3.2 0.1 82 602
+ 1.84566 0 2 tcp 1000 ------- 2 0.1 3.2 102 611
```

Problem: Tracing needs vary widely

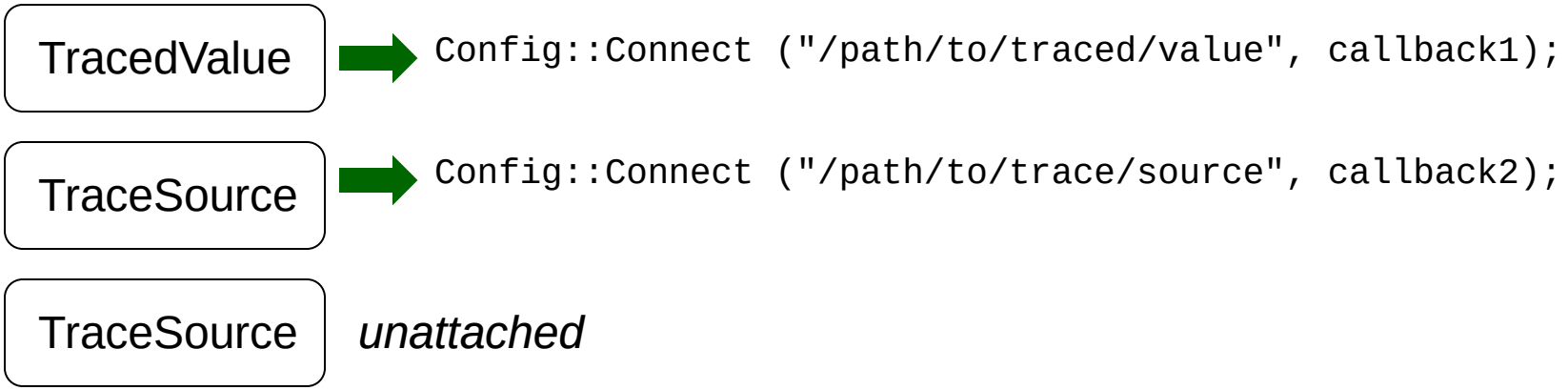
- would like to change tracing output without editing the core
- would like to support multiple outputs

Tracing overview

- Simulator provides a set of pre-configured trace sources
  - Users may edit the core to add their own
- Users provide trace sinks and attach to the trace source
  - Simulator core provides a few examples for common cases
- Multiple trace sources can connect to a trace sink

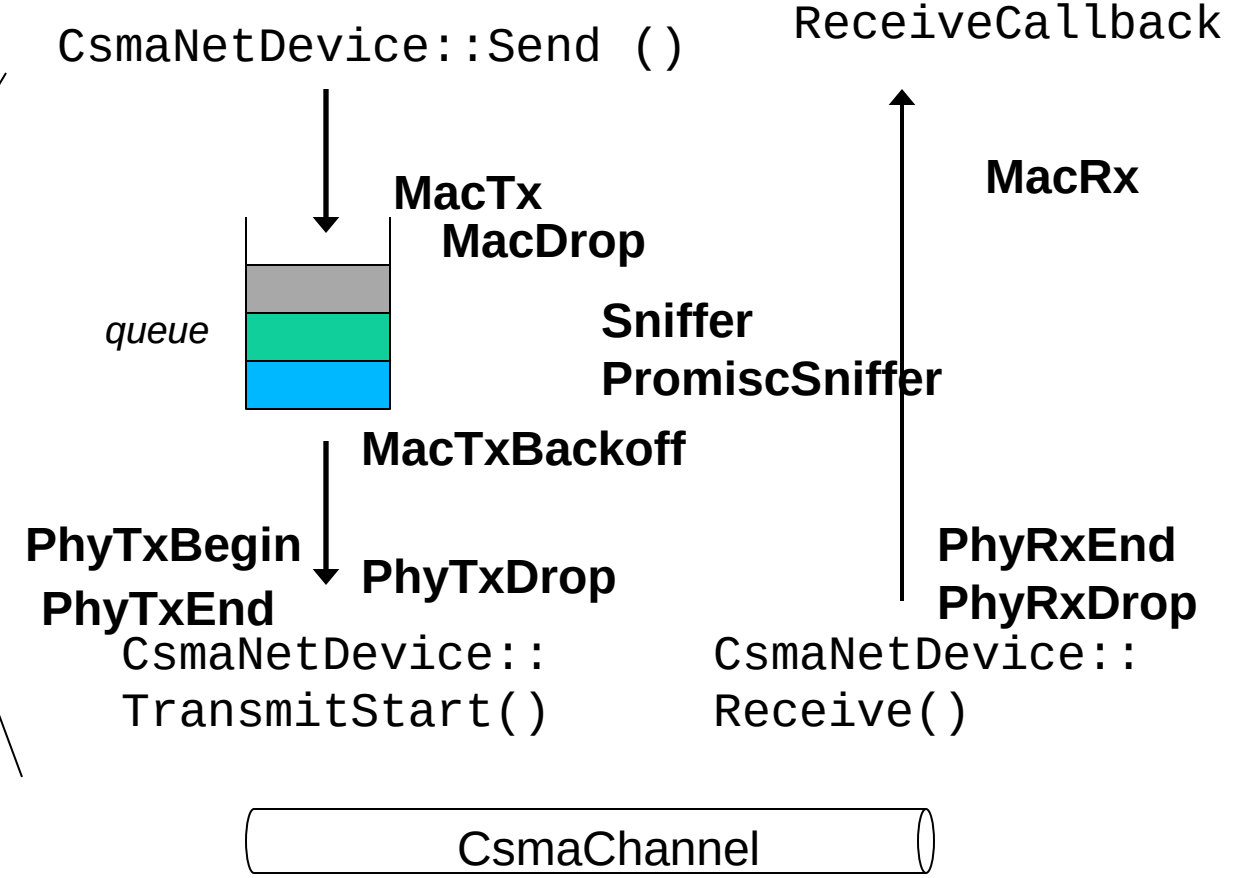
Tracing in ns-3

- ns-3 configures multiple 'TraceSource' objects (TracedValue, TracedCallback)
- Multiple types of 'TraceSink' objects can be hooked to these sources
- A special configuration namespace helps to manage access to trace sources



NetDevice trace hooks

- Example: CsmaNetDevice



Enabling tracing in your code

- examples/tutorial/third.cc

```
PointToPointHelper pointToPoint;
pointToPoint.SetDeviceAttribute ("DataRate", StringValue ("5Mbps"));
pointToPoint.SetChannelAttribute ("Delay", StringValue ("2ms"));

NetDeviceContainer p2pDevices;
p2pDevices = pointToPoint.Install (p2pNodes);

NodeContainer csmaNodes;
csmaNodes.Add (p2pNodes.Get (1));
csmaNodes.Create (nCsma);

CsmaHelper csma;
csma.SetChannelAttribute ("DataRate", StringValue ("100Mbps"));
csma.SetChannelAttribute ("Delay", TimeValue (NanoSeconds (6560)));
```

Device helpers provide common API for enabling pcap traces

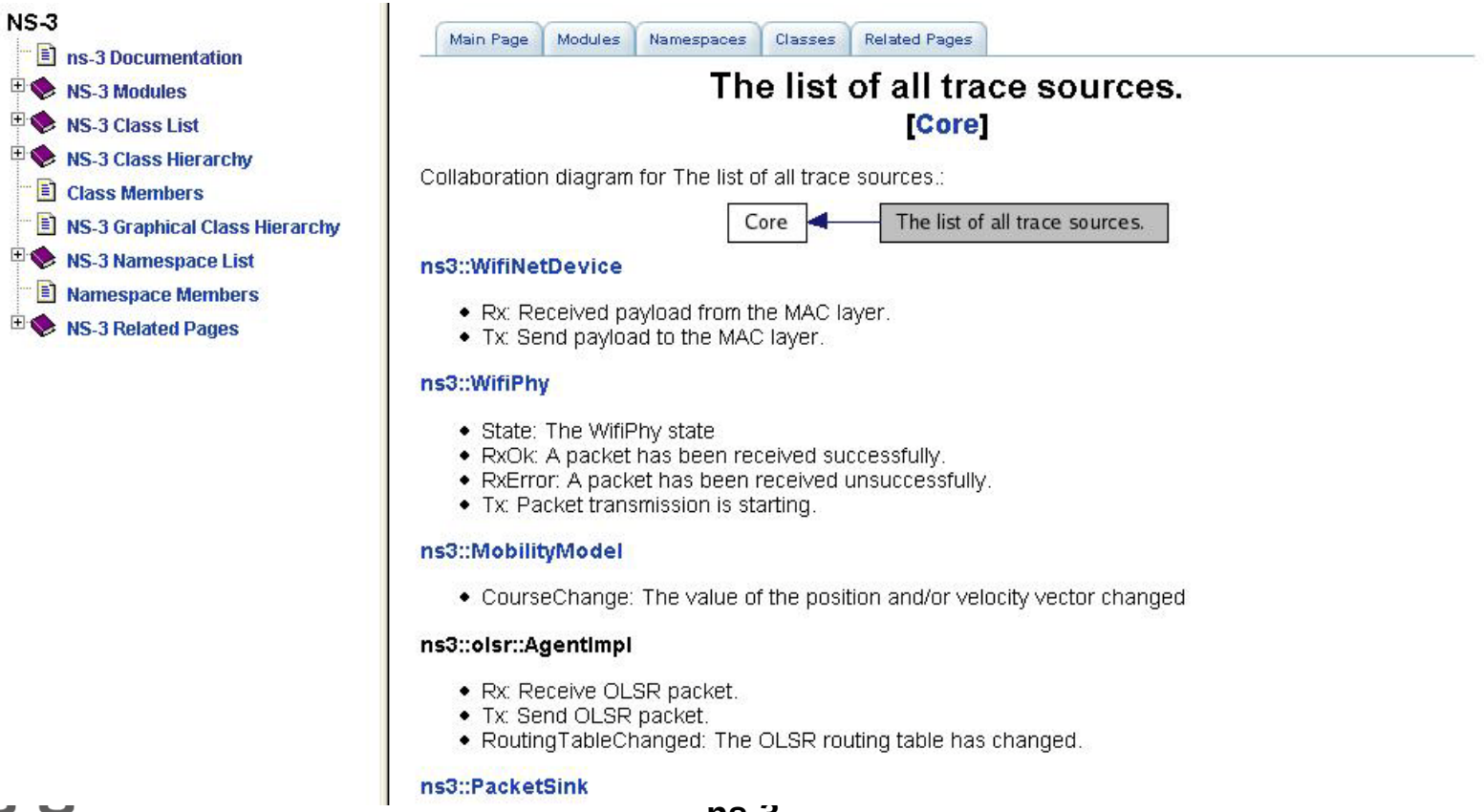
```
pointToPoint.EnablePcapAll ("third");
phy.EnablePcap ("third", apDevices.Get (0));
csma.EnablePcap ("third", csmaDevices.Get (0), true);
```

Global pcap tracing

Per-device pcap tracing

Discovering ns-3 trace sources

- various trace sources (e.g., packet receptions, state machine transitions) are plumbed through the system
- Organized with the rest of the attribute system



Basic tracing

- Helper classes hide the tracing details from the user, for simple trace types
  - ascii or pcap traces of devices

```
  if (tracing == true)
    {
      AsciiTraceHelper ascii;
      wifiPhy.EnableAsciiAll (ascii.CreateFileStream ("wifi-simple-adhoc-grid.tr"));
      wifiPhy.EnablePcap ("wifi-simple-adhoc-grid", devices);
      // Trace routing tables
      Ptr<OutputStreamWrapper> routingStream = Create<OutputStreamWrapper> ("wifi-simple-adhoc-
grid.routes", std::ios::out);
      olsr.PrintRoutingTableAllEvery (Seconds (2), routingStream);

      // To do-- enable an IP-level trace that shows forwarding events only
    }
```

Multiple levels of tracing

- Highest-level: Use built-in trace sources and sinks and hook a trace file to them
- Mid-level: Customize trace source/sink behavior using the tracing namespace
- Low-level: Add trace sources to the tracing namespace
  - Or expose trace source explicitly

Highest-level of tracing

- Highest-level: Use built-in trace sources and sinks and hook a trace file to them

```
// Also configure some tcpdump traces; each interface will be traced
// The output files will be named
// simple-point-to-point.pcap-<nodeId>-<interfaceId>
// and can be read by the "tcpdump -r" command (use "-tt" option to
// display timestamps correctly)
PcapTrace pcaptrace ("simple-point-to-point.pcap");
pcaptrace.TraceAllIp ();
```

Mid-level of tracing

- Mid-level: Customize trace source/sink behavior using the tracing namespace

```
void
PcapTrace::TraceAllIp (void)
{
  NodeList::Connect ("/nodes/*/ipv4/(tx|rx)",
                     MakeCallback (&PcapTrace::LogIp, this));
}
```

Regular expression editing

Hook in a different trace sink

Asciitrace: under the hood

```
void
AsciiTrace::TraceAllQueues (void)
{
  Packet::EnableMetadata ();
  NodeList::Connect ("/nodes/*/devices/*/queue/enqueue",
                     MakeCallback (&AsciiTrace::LogDevQueueEnqueue, this));
  NodeList::Connect ("/nodes/*/devices/*/queue/dequeue",
                     MakeCallback (&AsciiTrace::LogDevQueueDequeue, this));
  NodeList::Connect ("/nodes/*/devices/*/queue/drop",
                     MakeCallback (&AsciiTrace::LogDevQueueDrop, this));
}
```

Lowest-level of tracing

- Low-level: Add trace sources to the tracing namespace

```
Config::Connect ("/NodeList/.../Source",
                 MakeCallback (&ConfigTest::ChangeNotification, this));
```

Review of topics covered

- Structure of an ns-3 program
- Fundamental classes
  - Nodes, NetDevices, Channels, Applications
- Node and device containers
- Helper APIs, and Install pattern
- Wifi and Internet stack architecture
- Attributes and default values
- Tracing

Animation and visualization

FlowMonitor

- Network monitoring framework found in `src/flow-monitor/`
- Goals:
  - detect all flows passing through network
  - stores metrics for analysis such as bitrates, duration, delays, packet sizes, packet loss ratios

G. Carneiro, P. Fortuna, M. Ricardo, "FlowMonitor-- a network monitoring framework for the Network Simulator ns-3," Proceedings of NSTools 2009.

FlowMonitor architecture

- Basic classes
  - FlowMonitor
  - FlowProbe
  - FlowClassifier
  - FlowMonitorHelper
- Ipv4 only

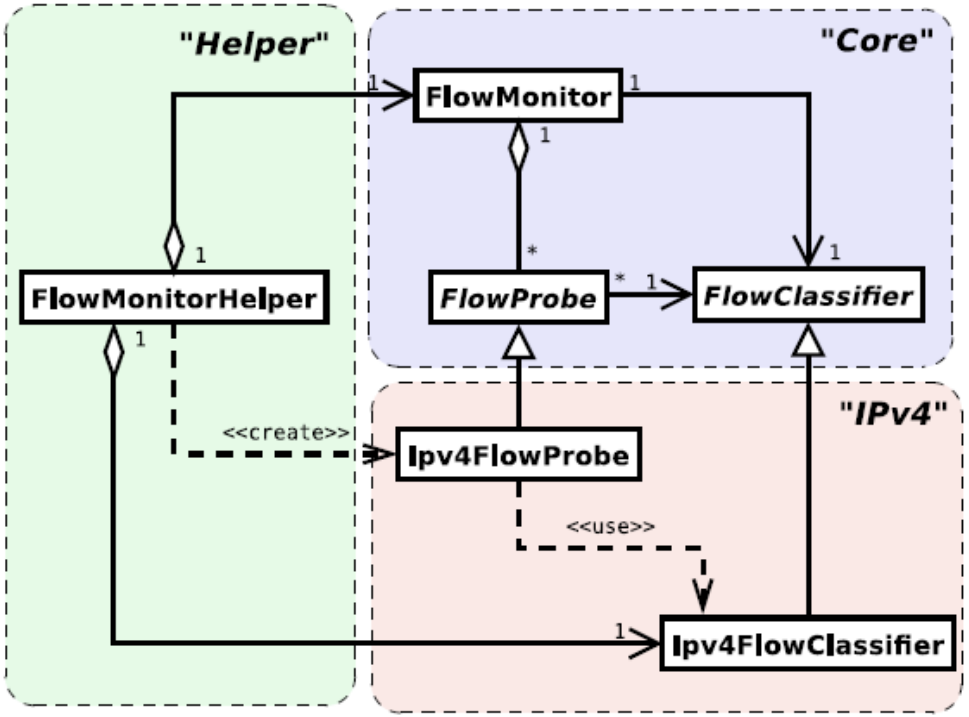


Figure credit: G. Carneiro, P. Fortuna, M. Ricardo, "FlowMonitor-- a network monitoring framework for the Network Simulator ns-3," Proceedings of NSTools 2009.

FlowMonitor statistics

- Statistics gathered

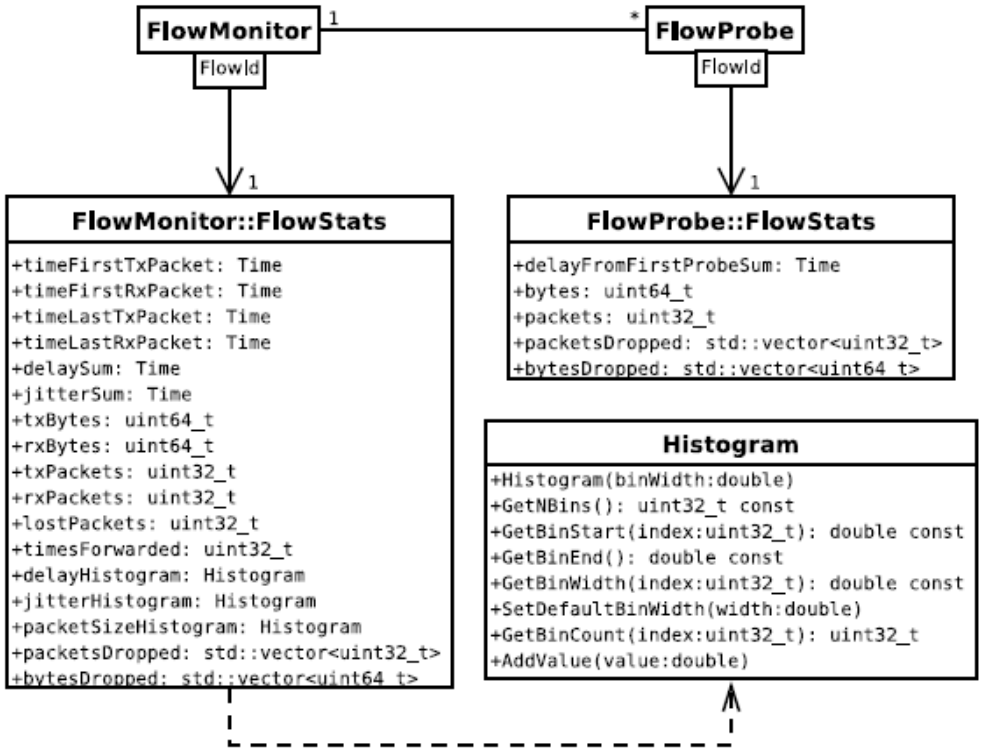


Figure credit: G. Carneiro, P. Fortuna, M. Ricardo, "FlowMonitor-- a network monitoring framework for the Network Simulator ns-3," Proceedings of NSTools 2009.

FlowMonitor configuration

- `example/wireless/wifi-hidden-terminal.cc`

```
// 8. Install FlowMonitor on all nodes
FlowMonitorHelper flowmon;
Ptr<FlowMonitor> monitor = flowmon.InstallAll ();

// 9. Run simulation for 10 seconds
Simulator::Stop (Seconds (10));
Simulator::Run ();

// 10. Print per flow statistics
monitor->CheckForLostPackets ();
Ptr<Ipv4FlowClassifier> classifier = DynamicCast<Ipv4FlowClassifier> (flowmon.GetClassifier ());
std::map<FlowId, FlowMonitor::FlowStats> stats = monitor->GetFlowStats ();
for (std::map<FlowId, FlowMonitor::FlowStats>::const_iterator i = stats.begin (); i != stats.end (); ++i)
  {
    // first 2 FlowIds are for ECHO apps, we don't want to display them
    if (i->first > 2)
      {
        Ipv4FlowClassifier::FiveTuple t = classifier->FindFlow (i->first);
        std::cout << "Flow " << i->first - 2 << " (" << t.sourceAddress << " -> " << t.destinationAddress << ")\n";
        std::cout << "  Tx Bytes:   " << i->second.txBytes << "\n";
        std::cout << "  Rx Bytes:   " << i->second.rxBytes << "\n";
        std::cout << "  Throughput: " << i->second.rxBytes * 8.0 / 10.0 / 1024 / 1024  << " Mbps\n";
      }
  }
```

FlowMonitor output

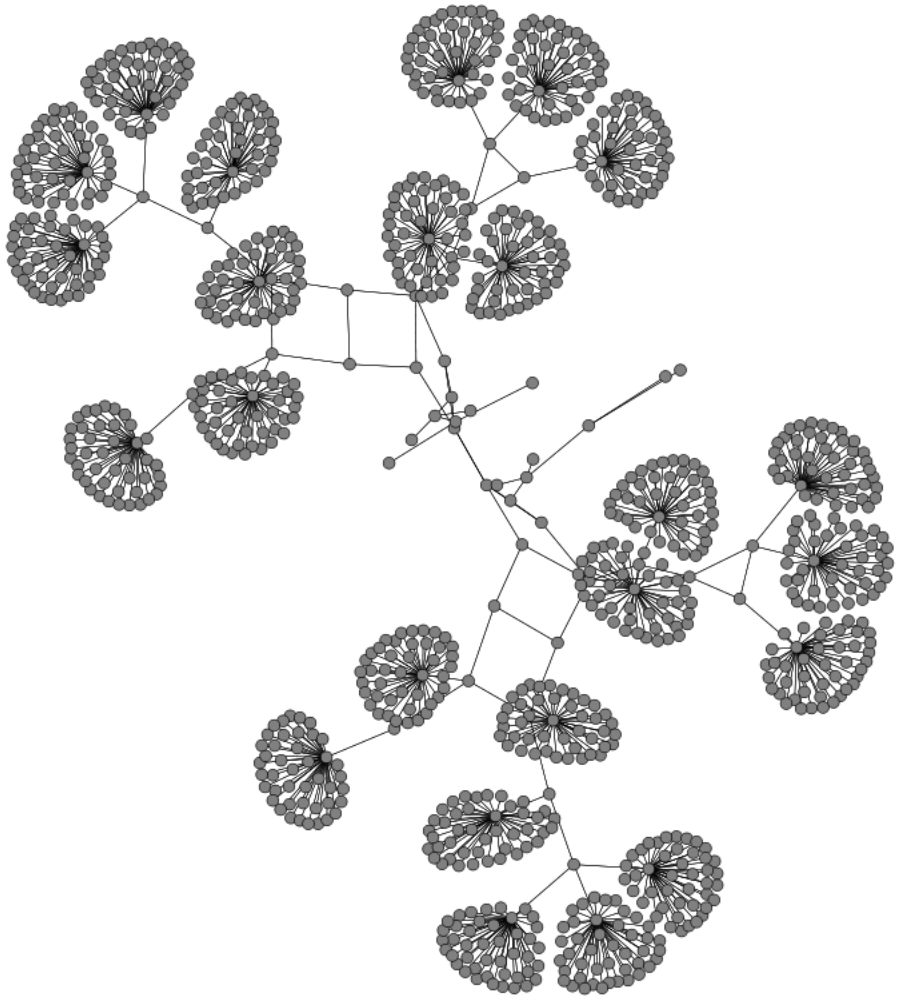
- This program exports statistics to stdout
- Other examples integrate with PyViz

```
Hidden station experiment with RTS/CTS disabled:
Flow 1 (10.0.0.1 -> 10.0.0.2)
  Tx Bytes:   3847500
  Rx Bytes:   316464
  Throughput: 0.241443 Mbps
Flow 2 (10.0.0.3 -> 10.0.0.2)
  Tx Bytes:   3848412
  Rx Bytes:   336756
  Throughput: 0.256924 Mbps
------------------------------------------------
Hidden station experiment with RTS/CTS enabled:
Flow 1 (10.0.0.1 -> 10.0.0.2)
  Tx Bytes:   3847500
  Rx Bytes:   306660
  Throughput: 0.233963 Mbps
Flow 2 (10.0.0.3 -> 10.0.0.2)
  Tx Bytes:   3848412
  Rx Bytes:   274740
  Throughput: 0.20961 Mbps
```

PyViz overview

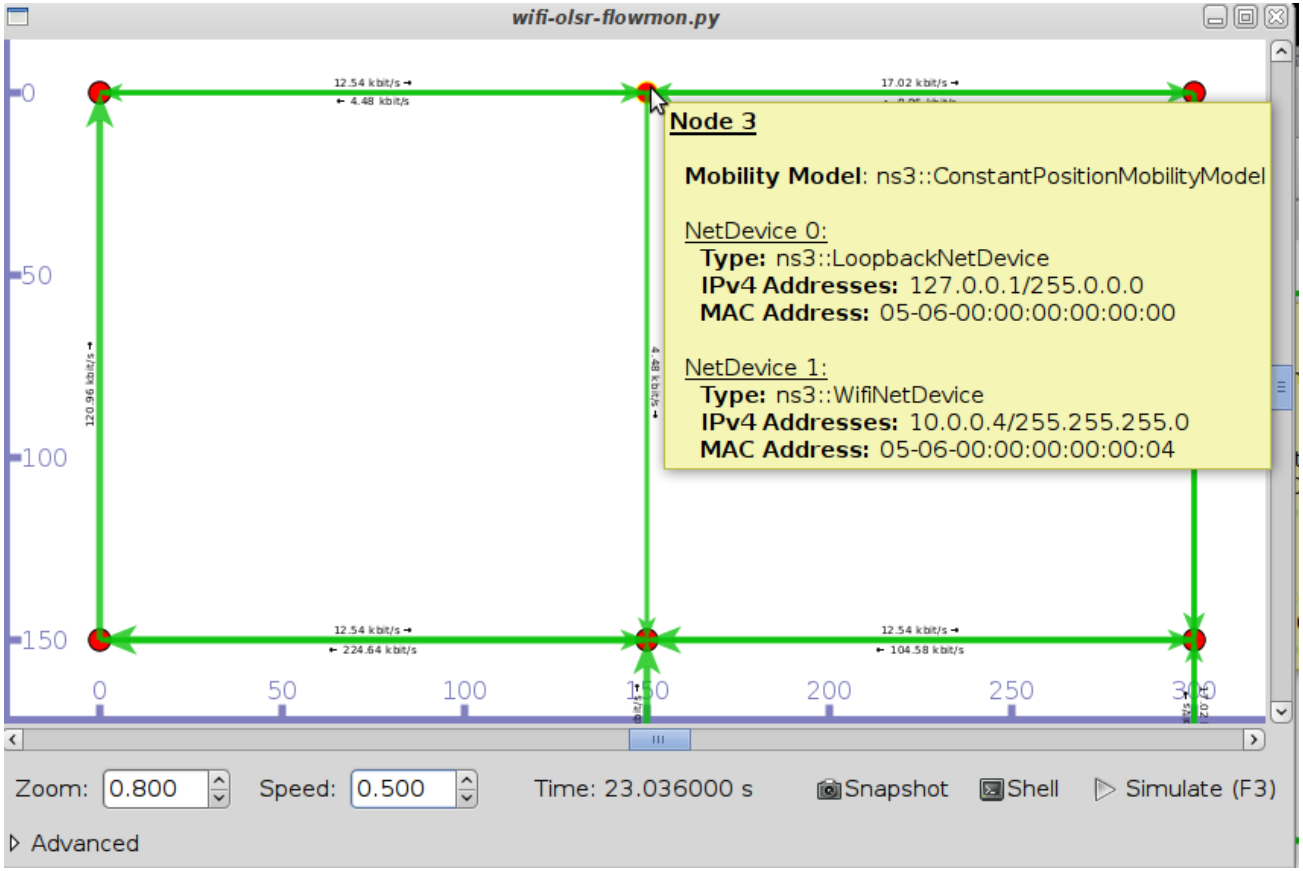
- Developed by Gustavo Carneiro
- Live simulation visualizer (no trace files)
- Useful for debugging
  - mobility model behavior
  - where are packets being dropped?
- Built-in interactive Python console to debug the state of running objects
- Works with Python and C++ programs

Pyviz screenshot (Graphviz layout)



Pyviz and FlowMonitor

- src/flow-monitor/examples/wifi-olsr-flowmon.py



Enabling PyViz in your simulations

- Make sure PyViz is enabled in the build

```
SQlite stats data output      : not enabled (library 'sqlite3' not found)
Tap Bridge                    : enabled
PyViz visualizer              : enabled
Use sudo to set suid bit      : not enabled (option --enable-sudo not selected)
```

- If program supports CommandLine parsing, pass the option

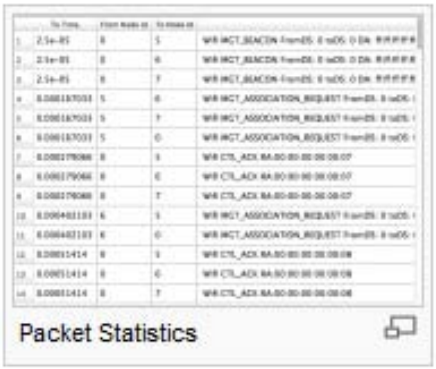
  `--SimulatorImplementationType=`

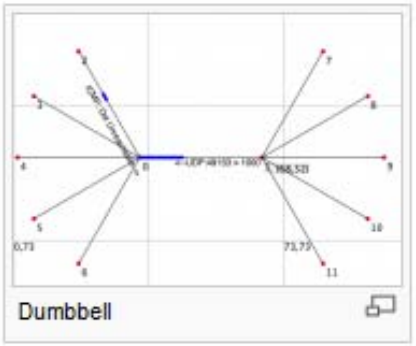
  `ns3::VisualSimulatorImpl`

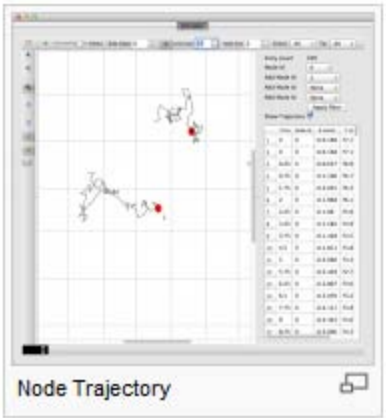
- Alternatively, pass the "--vis" option

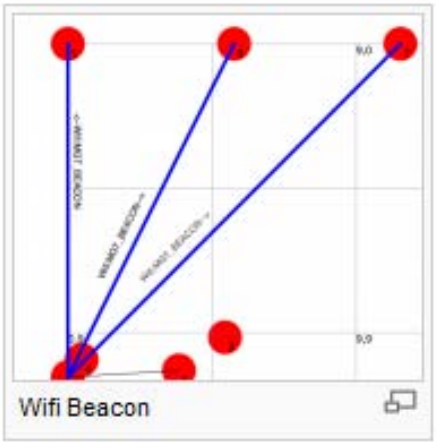
NetAnim

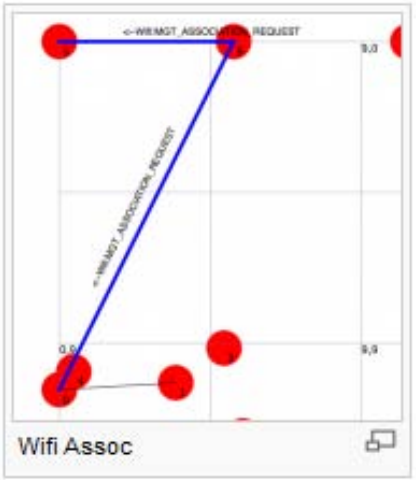
- "NetAnim" by George Riley and John Abraham

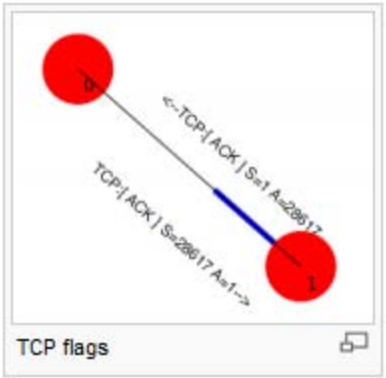












NetAnim key features

- Animate packets over wired-links and wireless-links
  - limited support for LTE traces
- Packet timeline with regex filter on packet meta-data.
- Node position statistics with node trajectory plotting (path of a mobile node).
- Print brief packet-meta data on packets

Writing and debugging your own examples

Writing and debugging new programs

- Choosing between Python and C++
- Reading existing code
- Understanding and controlling logging code
- Error conditions
- Running programs through a debugger

Python bindings

- ns-3 uses the 'pybindgen' tool to generate Python bindings for the underlying C++ libraries
- Existing bindings are typically found in the bindings/ directory of a module
- Some methods are not provided in Python (e.g. hooking trace sources)
- Generating new bindings requires a toolchain documented on the ns-3 web site

Reading existing code

- Much insight can be gained from reading ns-3 examples and tests, and running them yourselves
- Many core features of ns-3 are only demonstrated in the core test suite (src/core/test)
- Stepping through code with a debugger can be done, but callbacks and templates make it more challenging than usual

Debugging support

- Assertions: NS_ASSERT (expression);
  - Aborts the program if expression evaluates to false
  - Includes source file name and line number
- Unconditional Breakpoints: NS_BREAKPOINT ();
  - Forces an unconditional breakpoint, compiled in
- Debug Logging (not to be confused with tracing!)
  - Purpose
    - Used to trace code execution logic
    - For debugging, not to extract results!
  - Properties
    - NS_LOG* macros work with C++ IO streams
    - E.g.: NS_LOG_UNCOND (”I have received ” << p->GetSize () << ” bytes”);
    - NS_LOG macros evaluate to nothing in optimized builds
    - When debugging is done, logging does not get in the way of execution performance

Debugging support (cont.)

- Logging levels:
  - NS_LOG_ERROR (...): serious error messages only
  - NS_LOG_WARN (...): warning messages
  - NS_LOG_DEBUG (...): rare ad-hoc debug messages
  - NS_LOG_INFO (...): informational messages (eg. banners)
  - NS_LOG_FUNCTION (...):function tracing
  - NS_LOG_PARAM (...): parameters to functions
  - NS_LOG_LOGIC (...): control flow tracing within functions
- Logging ”components”
  - Logging messages organized by components
  - Usually one component is one .cc source file
  - NS_LOG_COMPONENT_DEFINE ("OlsrAgent");
- Displaying log messages. Two ways:
  - Programatically:
    - LogComponentEnable("OlsrAgent", LOG_LEVEL_ALL);
  - From the environment:
    - NS_LOG="OlsrAgent" ./my-program

Running C++ programs through gdb

- The gdb debugger can be used directly on binaries in the build directory
- An easier way is to use a waf shortcut

```
./waf --command-template="gdb %s" --run <program-name>
```

- Note: valgrind can be run similarly

```
./waf --command-template="valgrind %s" --run <program-name>
```

Testing

- Can you trust ns-3 simulations?
  - Can you trust *any* simulation?
    - Onus is on the simulation project to validate and document results
    - Onus is also on the researcher to verify results
- ns-3 strategies:
  - regression and unit tests
    - Aim for ***event-based*** rather than ***trace-based***
  - validation of models on testbeds
  - reuse of code

Test framework

- ns-3-dev is checked nightly on multiple platforms
  - Linux gcc-4.x, i386 and x86_64, OS X i386, FreeBSD and Cygwin (occasionally)
- `./test.py` will run regression tests

Walk through test code, test terminology (suite, case), and examples of how tests are run

Improving performance

- Debug vs optimized builds
  - ./waf -d debug configure
  - ./waf -d debug optimized
- Build ns-3 with static libraries
  - ./waf --enable-static
- Use different compilers (icc)
  - has been done in past, not regularly tested

Integrating other tools and libraries

Gnuplot

- `src/tools/gnuplot.{cc,h}`
- C++ wrapper around gnuplot
- classes:
  - `Gnuplot`
  - `GnuplotDataset`
    - `Gnuplot2dDataset, Gnuplot2dFunction`
    - `Gnuplot3dDataset, Gnuplot3dFunction`

Enabling gnuplot for your code

- `examples/wireless/wifi-clear-channel-cmu.cc`

```
CommandLine cmd;
cmd.Parse (argc, argv);

Gnuplot gnuplot = Gnuplot ("clear-channel.eps");

for (uint32_t i = 0; i < modes.size (); i++)
  {
    std::cout << modes[i] << std::endl;
    Gnuplot2dDataset dataset (modes[i]);
```

produce a plot file that will generate an EPS figure

one dataset per mode

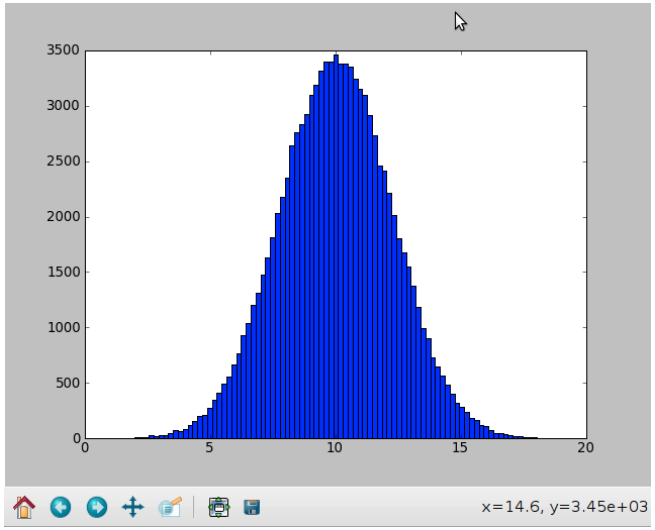
```
    uint32_t pktsRecvd = experiment.Run (wifi, wifiPhy, wifiMac, wifiChannel);
    dataset.Add (rss, pktsRecvd);
  }

gnuplot.AddDataset (dataset);
```

Add data to dataset

Add dataset to plot

Matplotlib

- src/core/examples/sample-rng-plot.py




```
# Demonstrate use of ns-3 as a random number generator integrated
# plotting tools; adapted from Gustavo Carneiro's ns-3 tutorial

import numpy as np
import matplotlib.pyplot as plt
import ns.core

# mu, var = 100, 225
rng = ns.core.NormalVariable(100.0, 225.0)
x = [rng.GetValue() for t in range(10000)]

# the histogram of the data
n, bins, patches = plt.hist(x, 50, normed=1, facecolor='g', alpha=0.75)

plt.title('ns-3 histogram')
plt.text(60, .025, r'$\mu=100,\ \sigma=15$')
plt.axis([40, 160, 0, 0.03])
plt.grid(True)
plt.show()
```

Other libraries

- ns-3 supports additional libraries (click, openflow, nsc)
- ns-3 has optional libraries (libxml2, gsl, mysql)
- both are typically enabled/disabled through the wscript
- users are free to write their own Makefiles or wscripts to do something special

Scaling to multiple machines

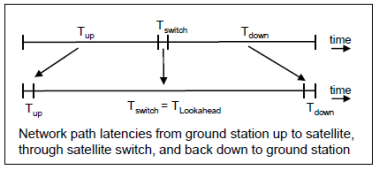
Overview

- Parallel and distributed discrete event simulation
  - Allows single simulation program to run on multiple interconnected processors
  - Reduced execution time! Larger topologies!
- Terminology
  - Logical process (LP)
  - Rank or system id

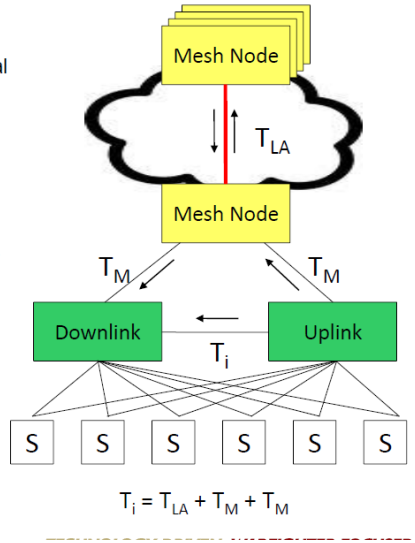
Simulation size record

- Simulation on a HPC cluster at the U.S. Mobile Network Modeling Institute (2011) *
  - **176 cores, 3 TB** of memory
  - **360,448,000** simulated nodes
  - **413,704.52** packet receive events per second [wall-clock]

- Each NS-3 Federate only instantiates its own subnets, a "mesh" node, and stubs for external mesh nodes
  - Number of PTP links: $N^2 \rightarrow N$
  - Requires interface re-numbering
- Static routing for unicast & multicast
- Inter-federate latency maximized
  - Time from uplink and downlink latencies and moved into satellite switching latency
  - Intra-federate latency between subnets matches inter-federate latency
- Scenario run for 20 minutes of simulated time

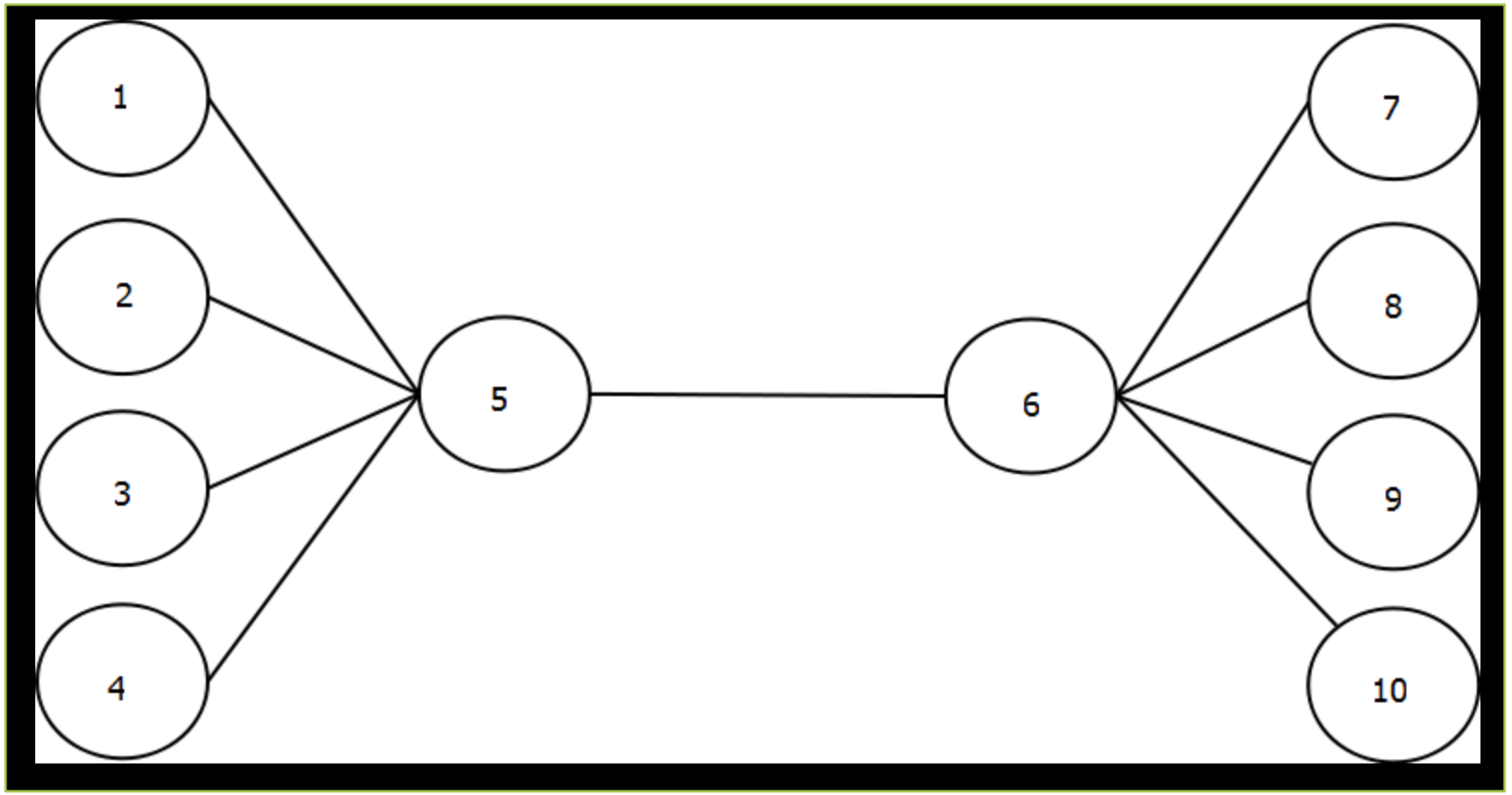


Network path latencies from ground station up to satellite, through satellite switch, and back down to ground station

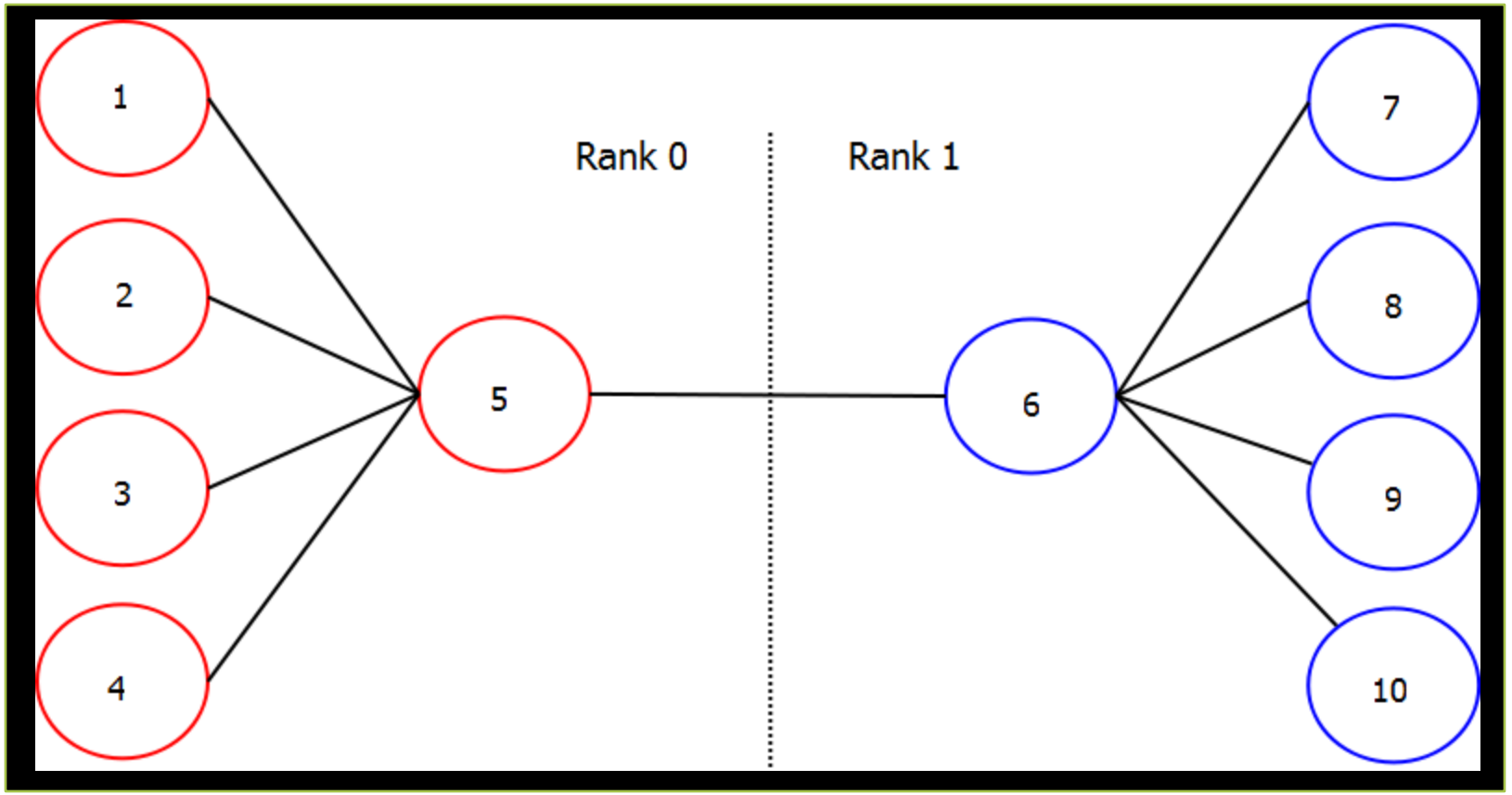


* K. Renard et al, "A Performance and Scalability Evaluation of the NS-3 Distributed Scheduler. Proceedings of WNS3 2012.

Quick and Easy Example



Quick and Easy Example



Implementation Details

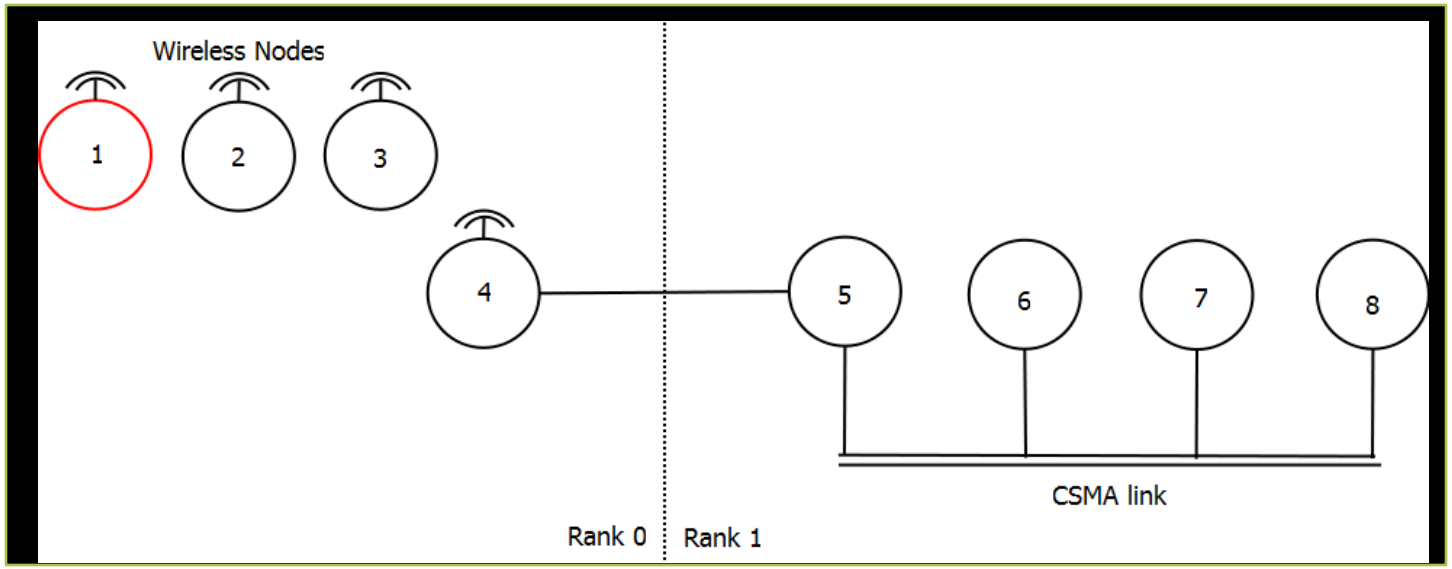
- LP communication
  - Message Passing Interface (MPI) standard
  - Send/Receive time-stamped messages
  - MpiInterface in ns-3
- Synchronization
  - Conservative algorithm using lookahead
  - DistributedSimulator in ns-3

Implementation Details (cont.)

- Assigning rank
  - Currently handled manually in simulation script
  - Next step, MpiHelper for easier node/rank mapping
- Remote point-to-point links
  - Created automatically between nodes with different ranks through point-to-point helper
  - Packet sent across using MpiInterface

Implementation Details (cont.)

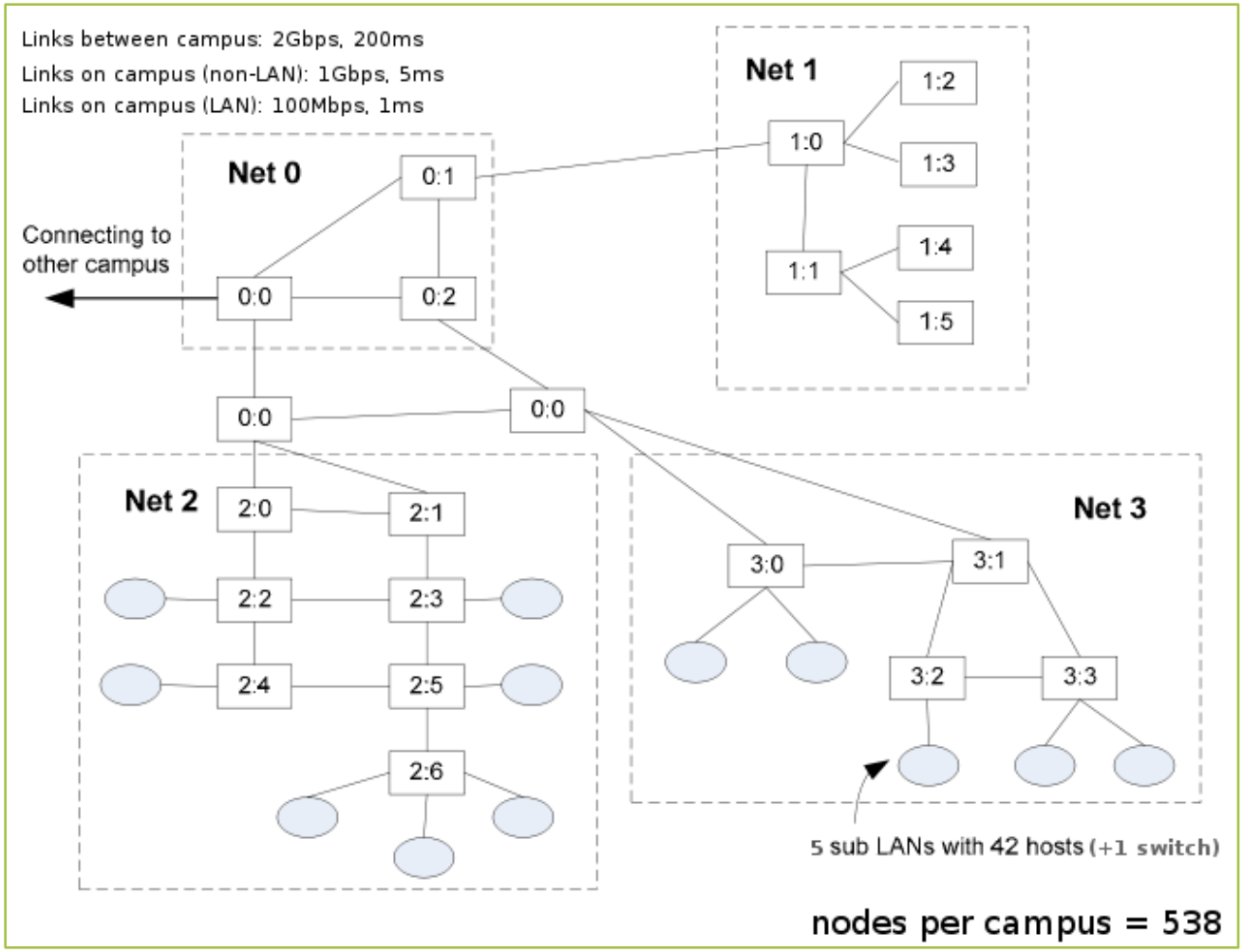
- Distributing the topology
  - All nodes created on all LPs, regardless of rank
  - Applications are only installed on LPs with target node



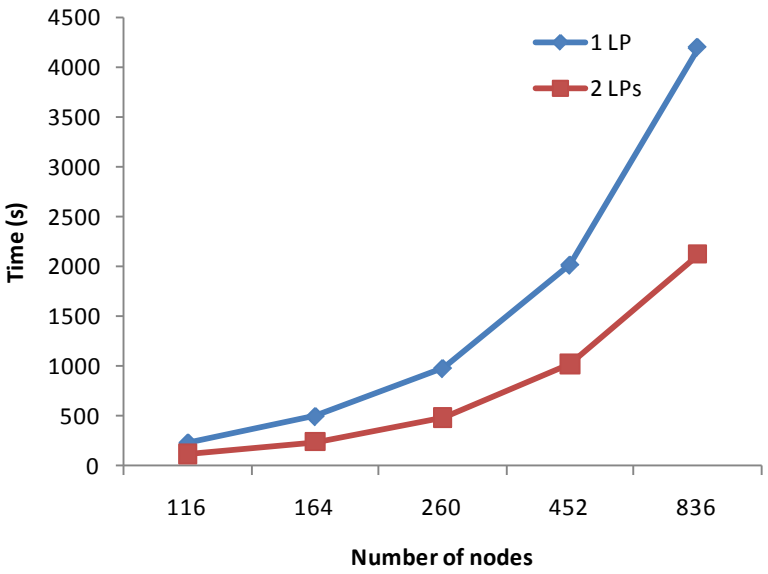
Performance Test

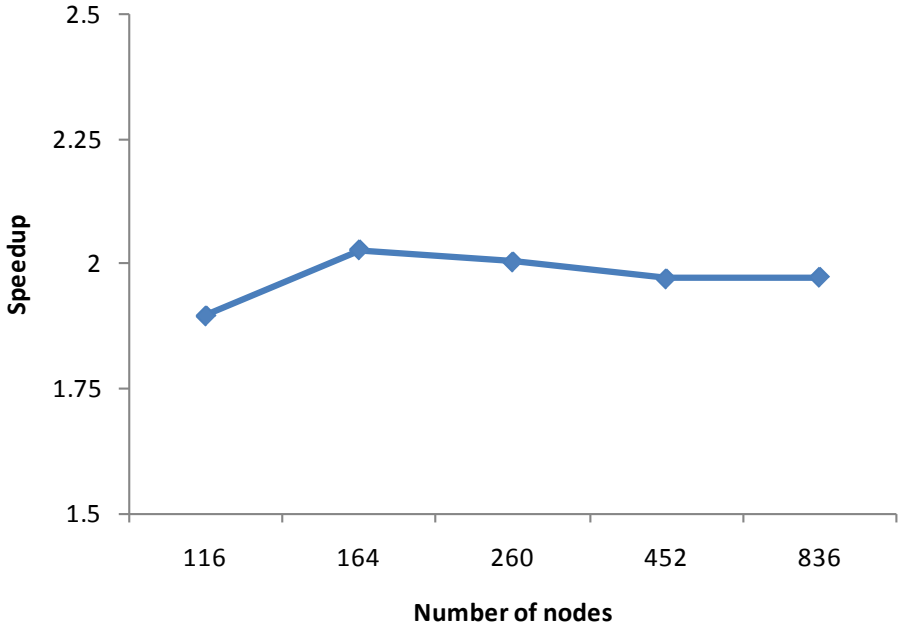
- DARPA NMS campus network simulation
  - Allows creation of very large topologies
  - Any number of campus networks are created and connected together
  - Different campus networks can be placed on different LPs
  - Tested with 2 CNs, 4 CNs, and 6 CNs

Campus Network Topology



2 Campus Networks





Summary

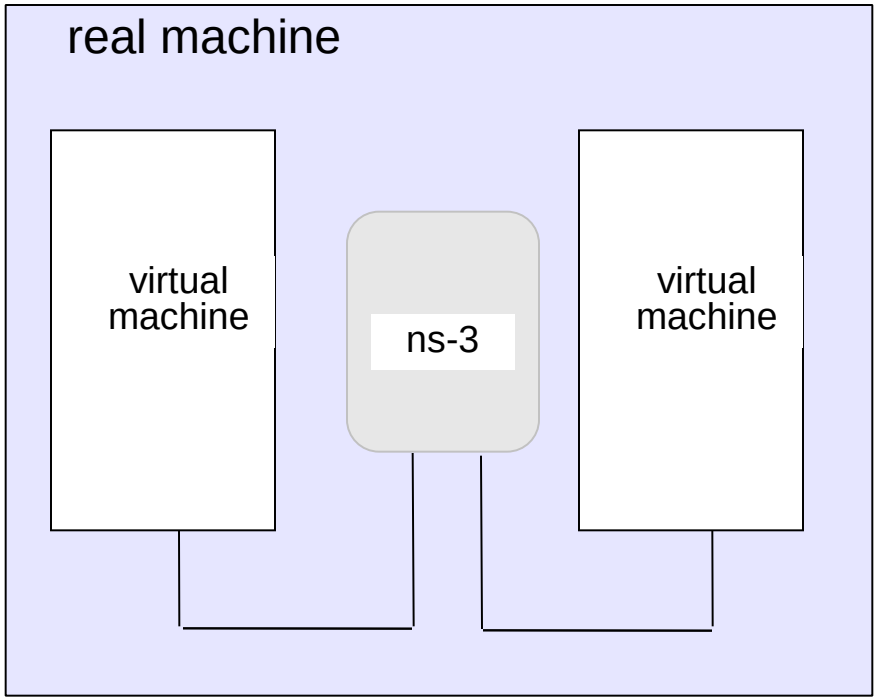
- Distributed simulation in ns-3 allows a user to run a single simulation in parallel on multiple processors
- By assigning a different rank to nodes and connecting these nodes with point-to-point links, simulator boundaries are created
- Simulator boundaries divide LPs, and each LP can be executed by a different processor
- Distributed simulation in ns-3 offers solid performance gains in time of execution for large topologies

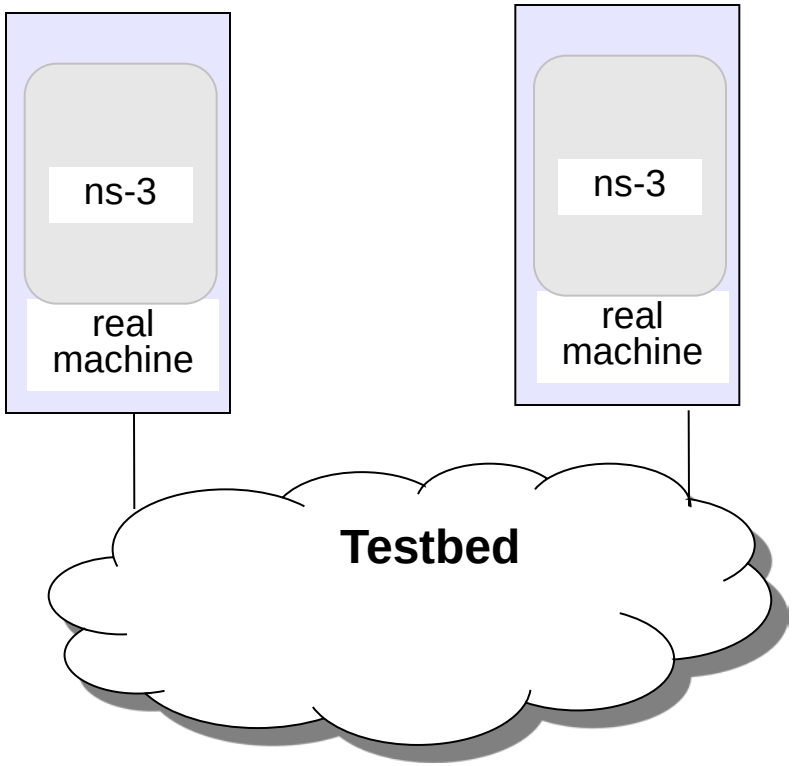
emulation and testbeds

Emulation support

- Support moving between simulation and testbeds or live systems
- A real-time scheduler, and support for two modes of emulation
  - `GlobalValue::Bind (“SimulatorImplementationType”, StringValue (“ns3::RealTimeSimulatorImpl”));`

ns-3 emulation modes



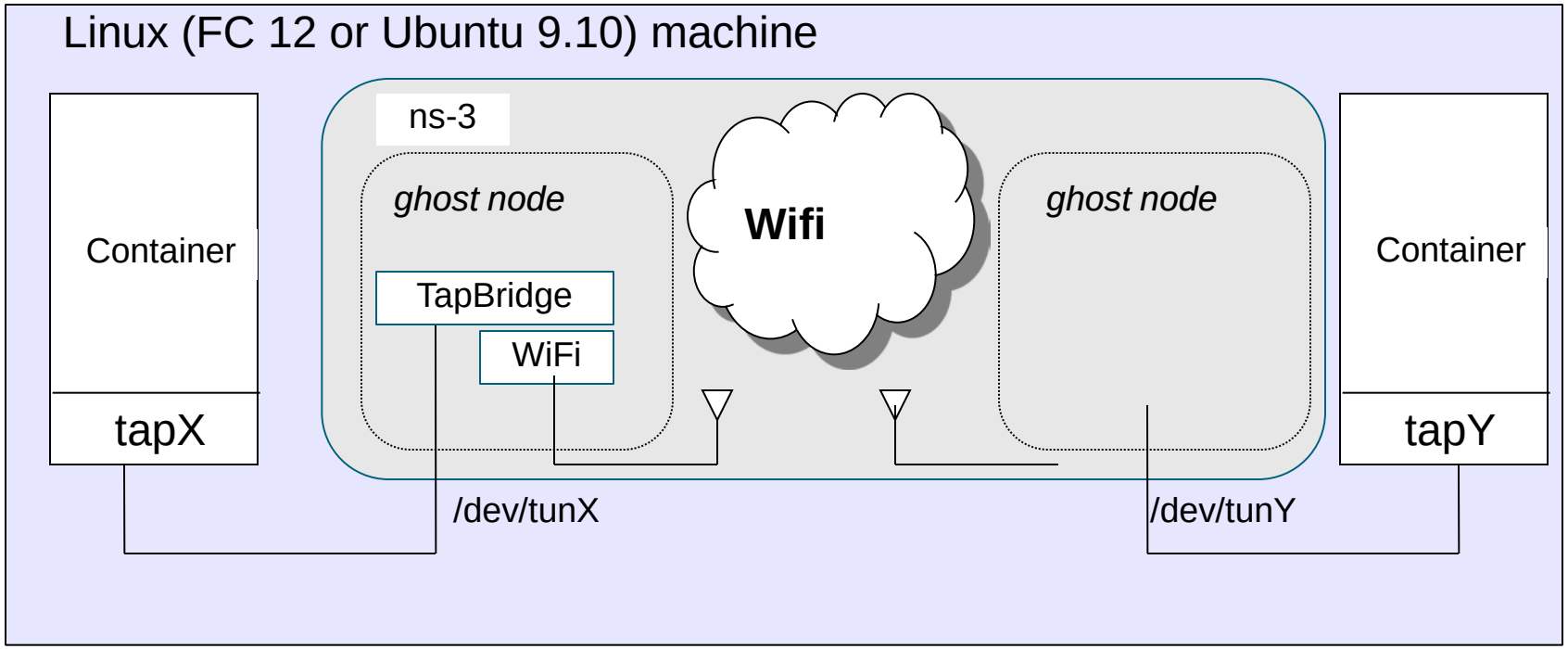


1) ns-3 interconnects real or virtual machines

2) testbeds interconnect ns-3 stacks

Various hybrids of the above are possible

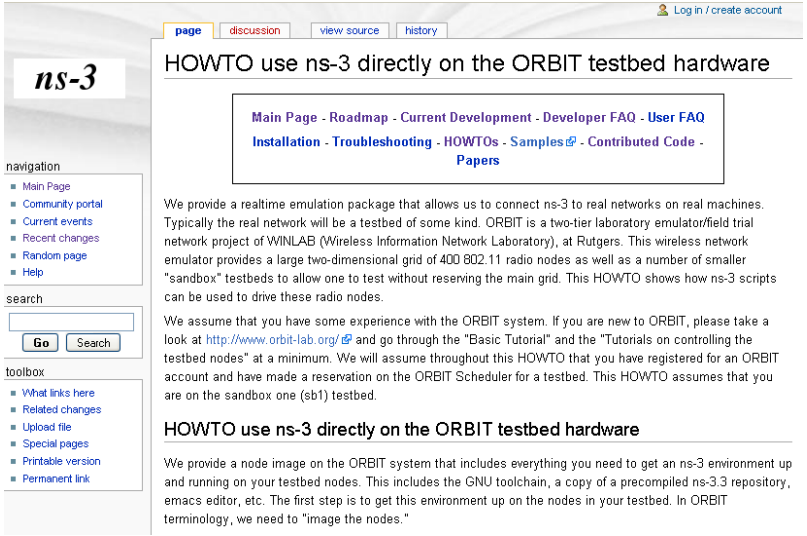
“Tap” mode: netns and ns-3 integration



Tap device pushed into namespaces; no bridging needed

Example: ORBIT and ns-3

- Support for use of Rutgers WINLAB ORBIT radio grid



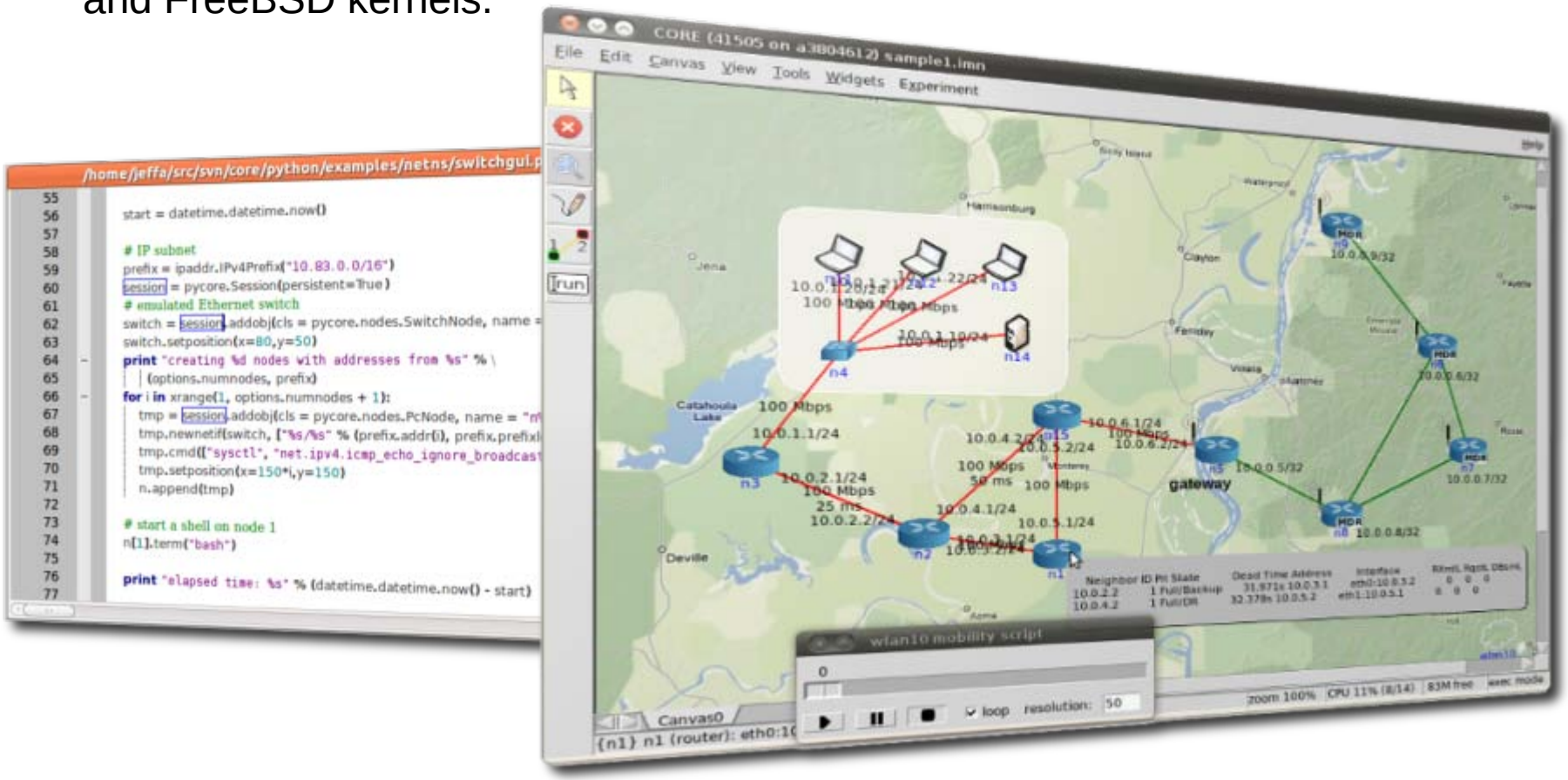
Issues

- Ease of use
  - Configuration management and coherence
  - Information coordination (two sets of state)
    - e.g. IP/MAC address coordination
  - Output data exists in two domains
  - Debugging
- Error-free operation (avoidance of misuse)
  - Synchronization, information sharing, exception handling
    - Checkpoints for execution bring-up
    - Inoperative commands within an execution domain
    - Deal with run-time errors
  - Soft performance degradation (CPU) and time discontinuities

Container-based virtual machines and ns-3

What is CORE?

- The Common Open Research Emulator (CORE) is a Python framework and GUI for emulating networks using lightweight Virtualization native to Linux and FreeBSD kernels.



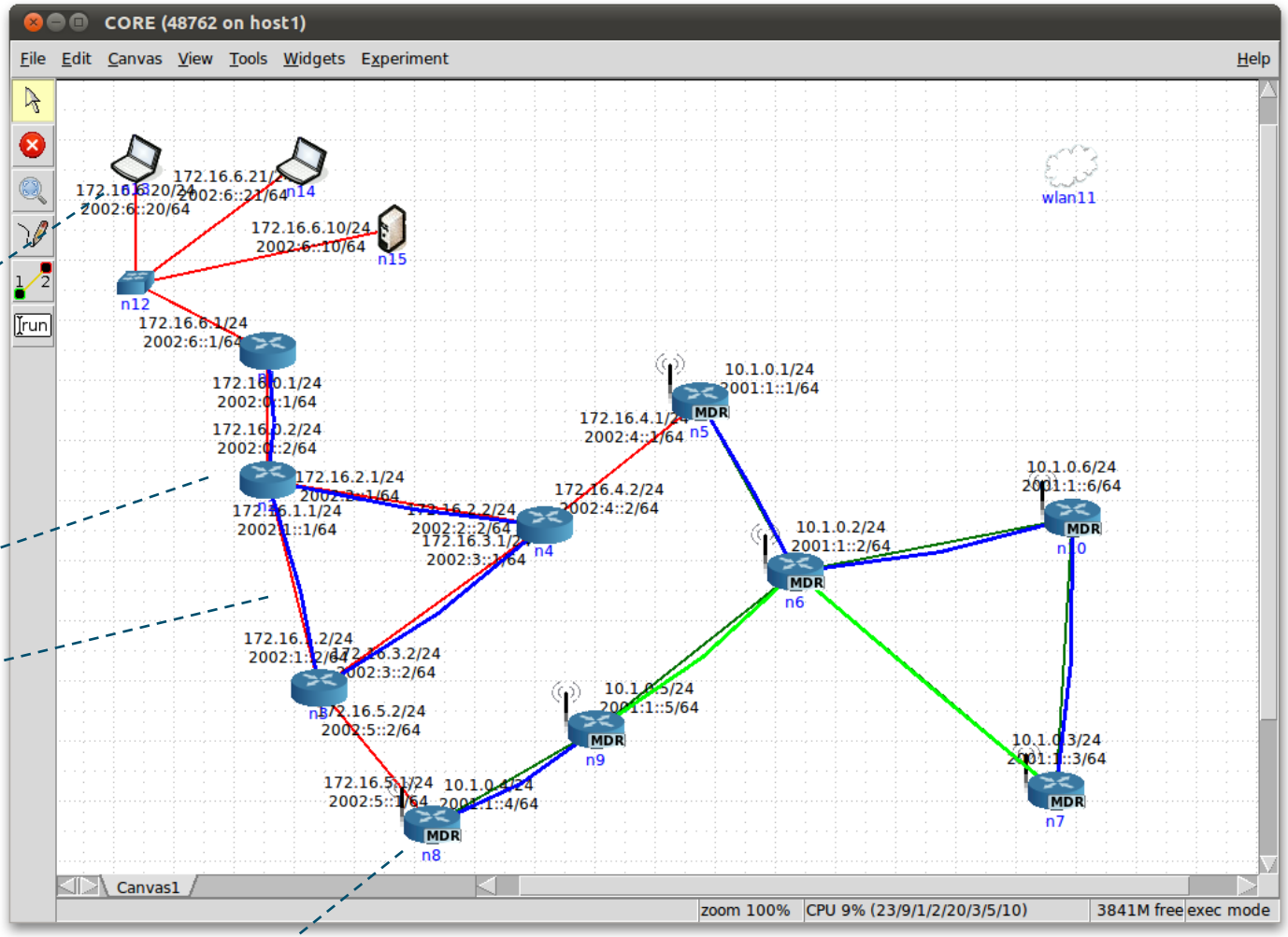
Screenshot

Lightweight VMs Double-click for shell

Wired networks

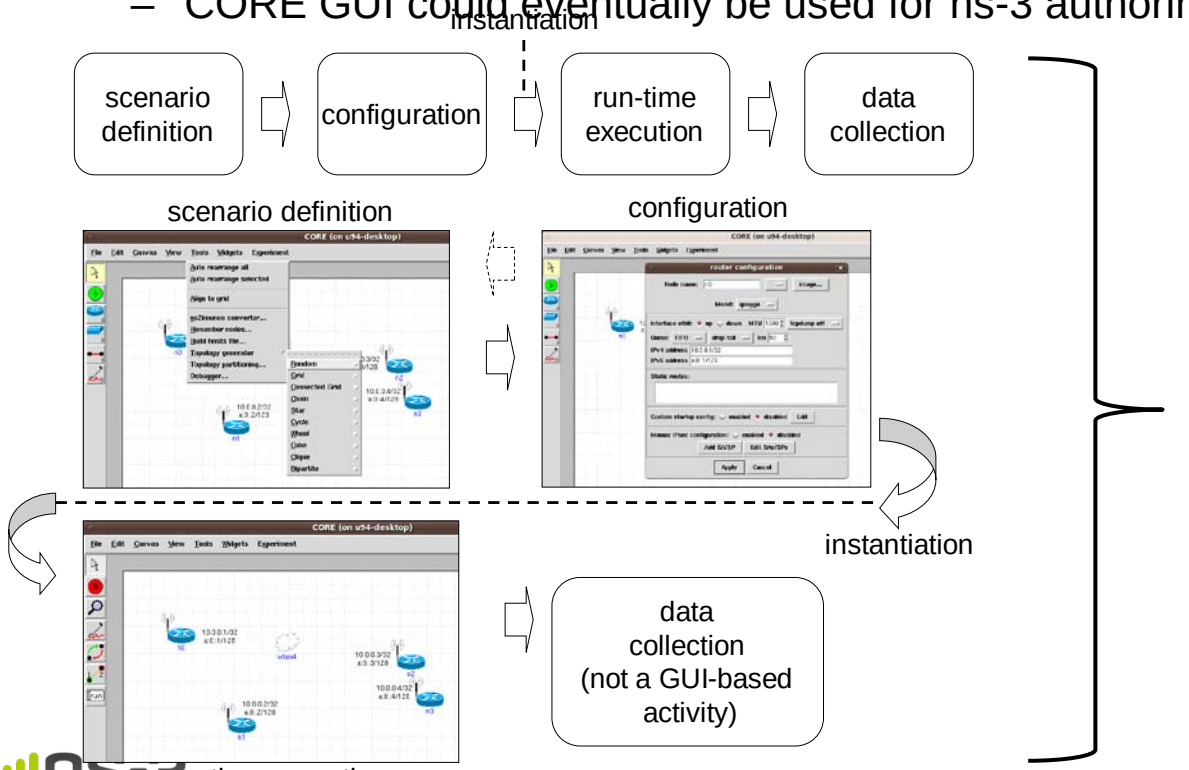
Visualize routing state

Wireless networks



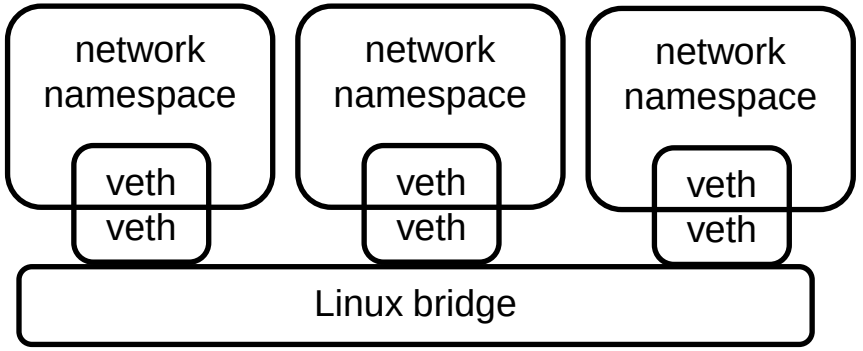
Technical Goals

- CORE provides Python libraries for using Linux network namespaces in network emulation experiments
  - CORE + ns-3 integrates realism of namespace with wireless device models
- CORE is a graphical controller that users find intuitive
  - CORE GUI could eventually be used for ns-3 authoring/visualization

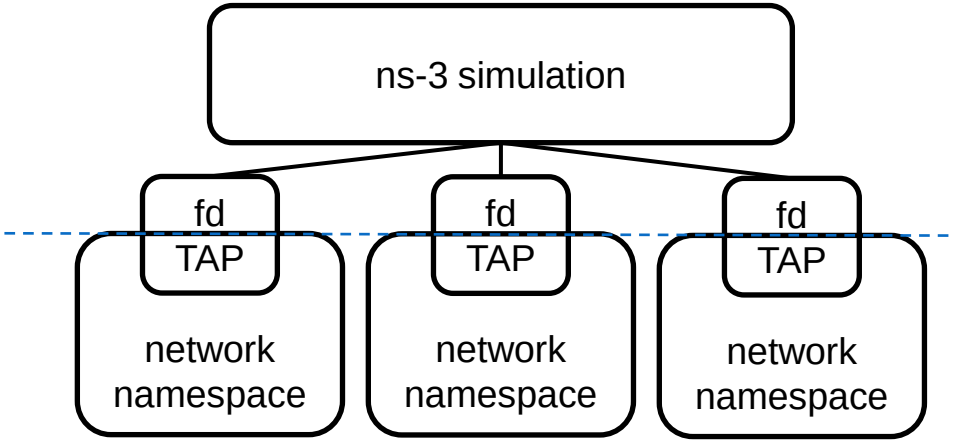


Virtual Interfaces

- Ordinary CORE
  - Virtual Ethernet pairs (veth) are installed into a namespace and joined to a bridge.
  - For wireless networks (WLANs), ebtables rules govern pairwise connectivity.

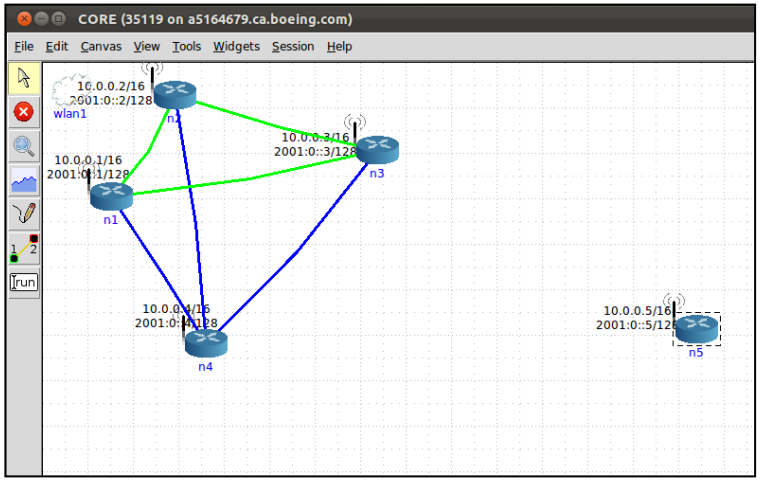


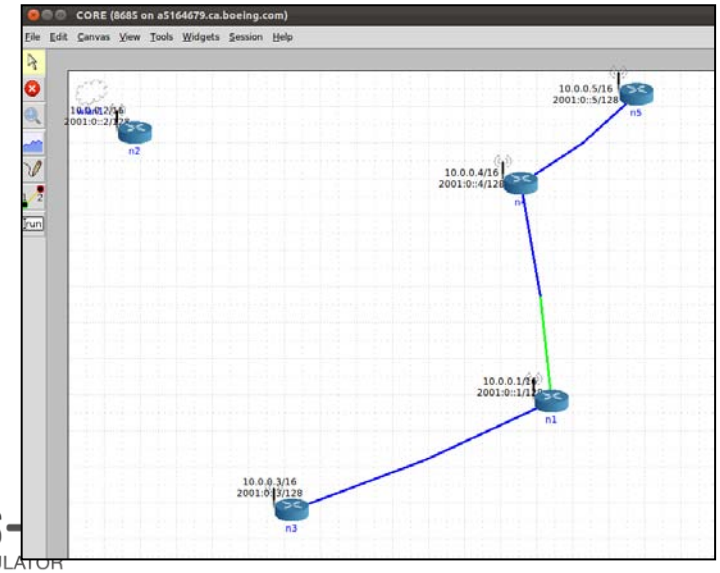
- CORE + ns-3
  - TUN/TAP device installed into a namespace, socket held by simulation.
  - Simulation runs with real-time scheduler.



Mobility demonstration

Canvas-based mobility
• ns-3 ConstantPosition MobilityModel
• users can drag nodes around and change topology





ns-3 mobility visualization
• ns-3 RandomWalk Mobility Model
• users can observe Linux namespace state (e.g. OSPF adjacencies) as nodes move in the ns-3 realm

Scaling time in virtualized environments

- Synchronized Network Emulation - RWTH Aachen University
  - Modified Xen
- VAN Testbed – Telcordia/CERDEC
  - Modified Xen
- Linux Time namespace - Jeff Dike (UML creator)
  - Add a time namespace to the Linux kernel, allowing for gettimeofday() offsets

Direct Code Execution

Goals

- Lightweight virtualization of kernel and application processes, interconnected by simulated networks
- Benefits:
  - Implementation realism in controlled topologies or wireless environments
  - Model availability
- Limitations:
  - Not as scalable as pure simulation
  - Runs in real-time
  - Integration of the two environments

Direct Code Execution

- Developed by Mathieu Lacage and Frederic Urbani, INRIA, Hajime Tazaki (WIDE)
- Run unmodified application binaries in ns-3
  - Also, can run entire Linux stack in ns-3

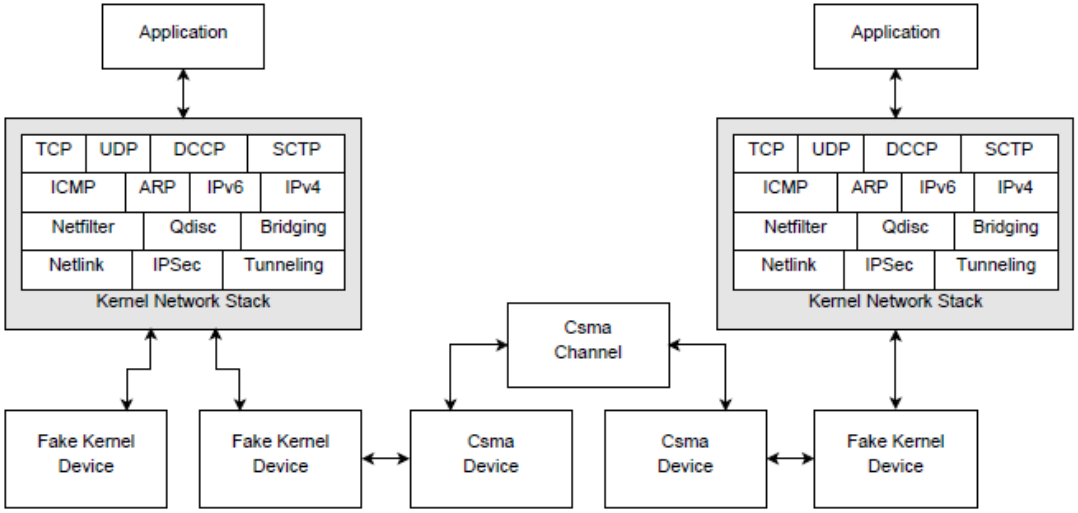


Figure 4.6: The Linux network stack running inside ns-3

Figure source: Mathieu Lacage

http://www-sop.inria.fr/members/Frederic.Urbani/ns3dceccnx/index.html

NEPI

Network Experiment Management Framework (NEPI)

- Network experiment management framework to automate experiment life-cycle
- Allows scenarios involving heterogeneous resources (ns-3, PlanetLab, netns, …)
- Wiki: http://nepi.inria.fr

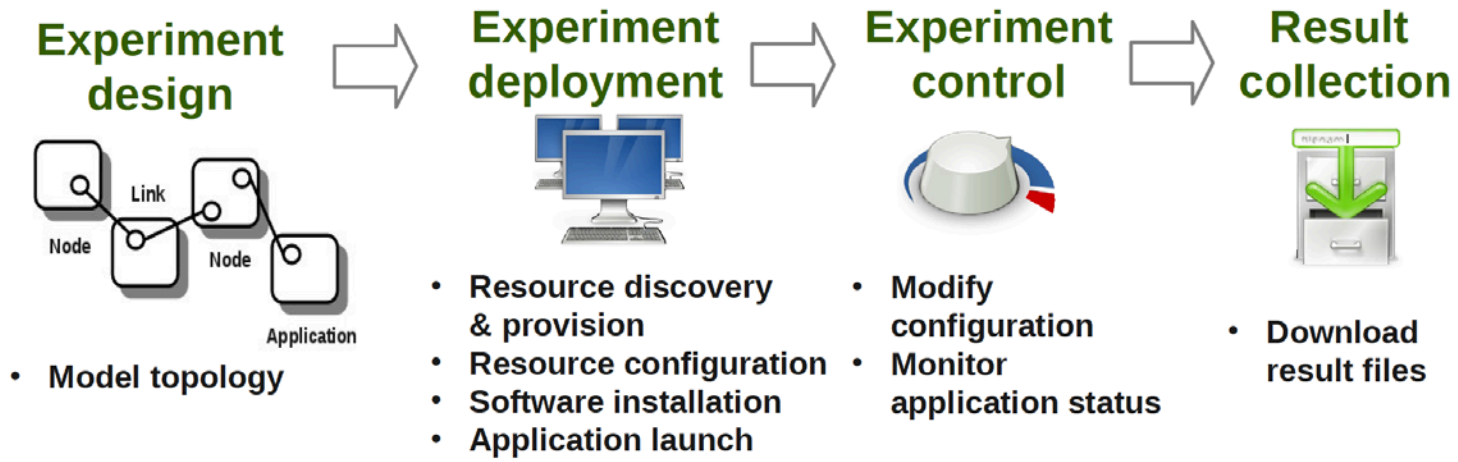


Figure source: Alina Quereilhac, INRIA

Getting Help and Getting Involved

Resources

Web site:

http://www.nsnam.org

Mailing list:

http://mailman.isi.edu/mailman/listinfo/ns-developers

IRC: #ns-3 at freenode.net

Tutorial:

http://www.nsnam.org/docs/tutorial/tutorial.html

Code server:

http://code.nsnam.org

Wiki:

http://www.nsnam.org/wiki/index.php/Main_Page

Questions?