NS-3 Tutorial

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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

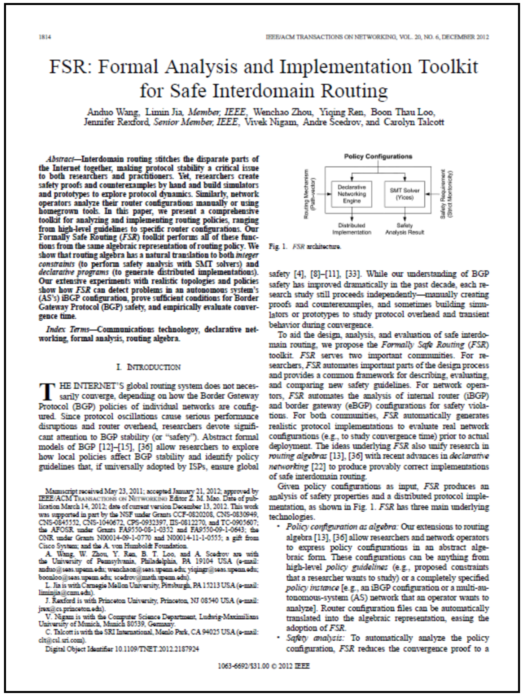
Preliminaries (cont.)

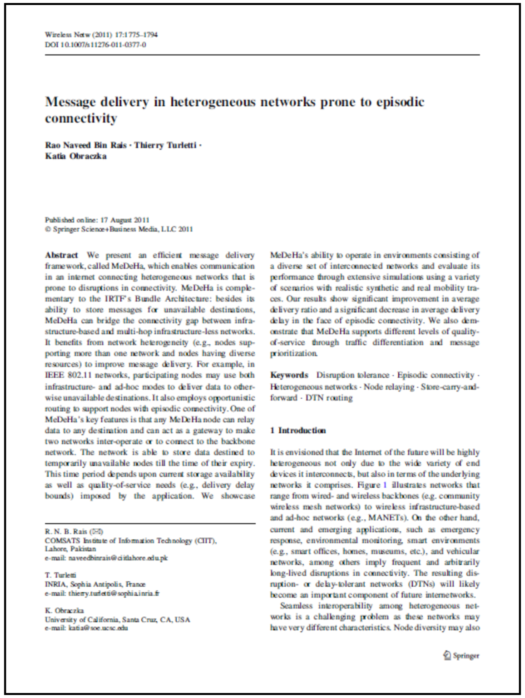
- Where do I get ns-3?
  - http://www.nsnam.org

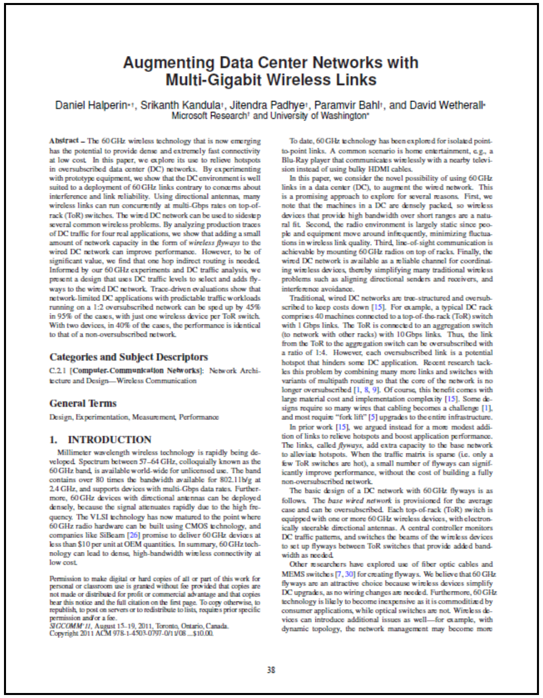
- Where do I get today's code?
  - http://www.nsnam.org/release/ns-allinone-3.16.tar.bz2

What have people done with ns-3?

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







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.

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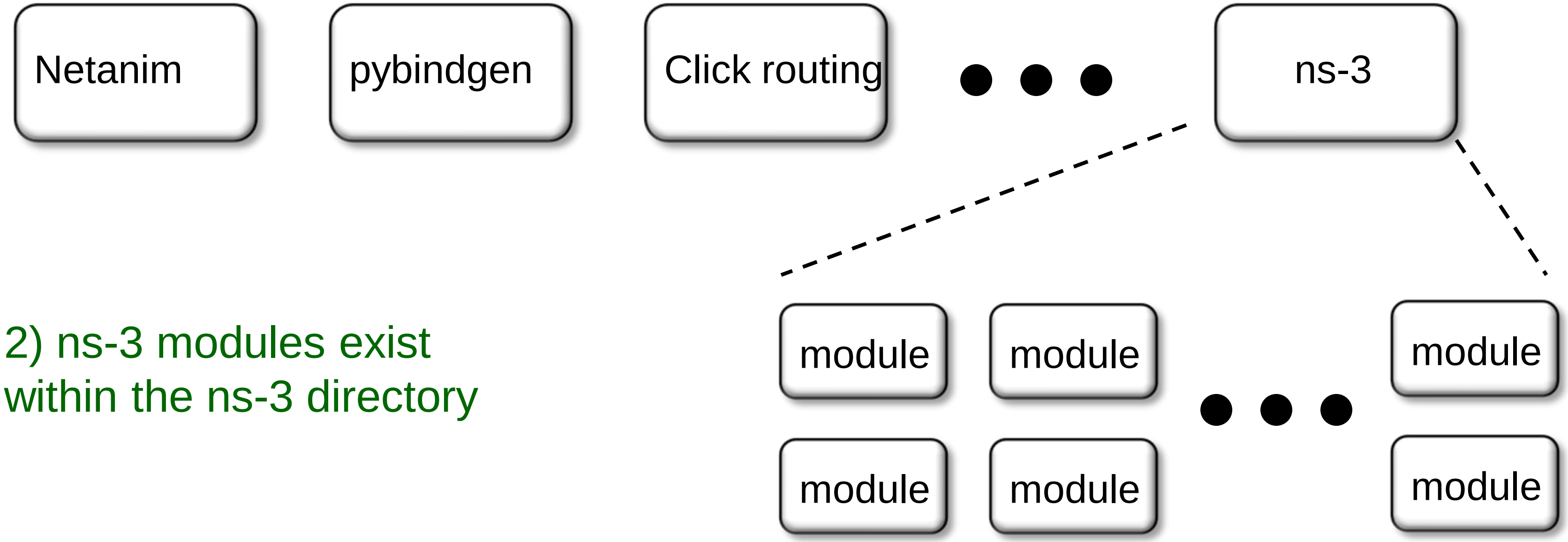
Software organization

- 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

devices

- bridge
- spectrum
- csma
- tap-bridge
- emu
- uan
- point-to-point
- virtual-net-device
- lte
- wifi
- mesh
- wimax

- applications
- internet (IPv4/v6)
- network
- core

- energy
- mpi
- mobility
- propagation

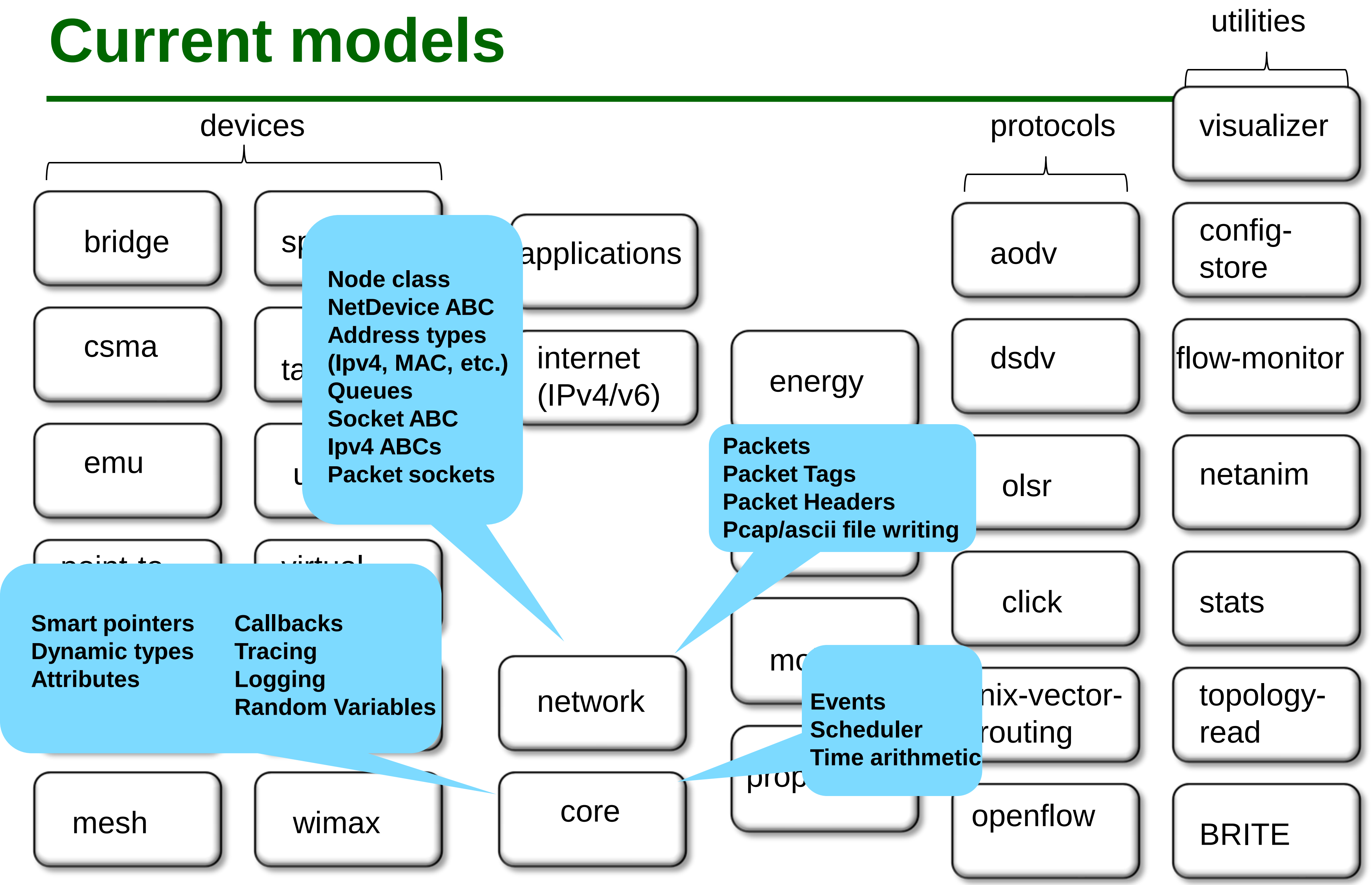
protocols

- aodv
- dsdv
- olsr
- click
- nix-vector-routing
- openflow

utilities

- visualizer
- config-store
- flow-monitor
- netanim
- stats
- topology-read
- BRITE

Current models



Module organization

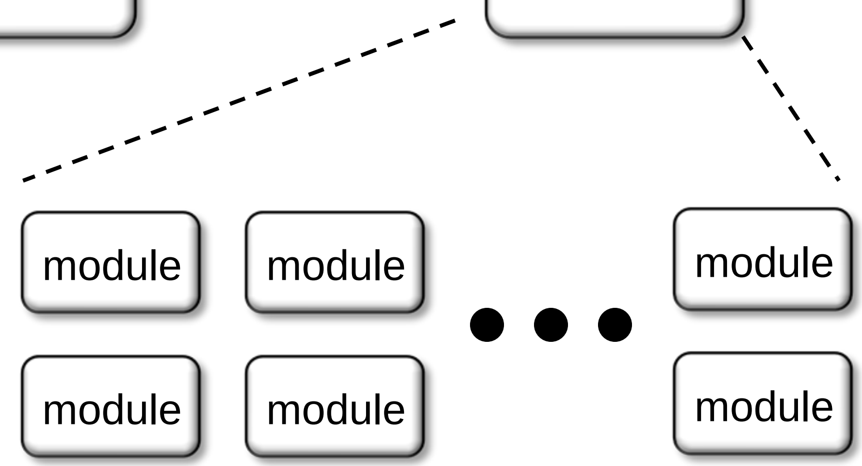
- models/
- examples/
- tests/
- bindings/
- doc/
- wscript

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

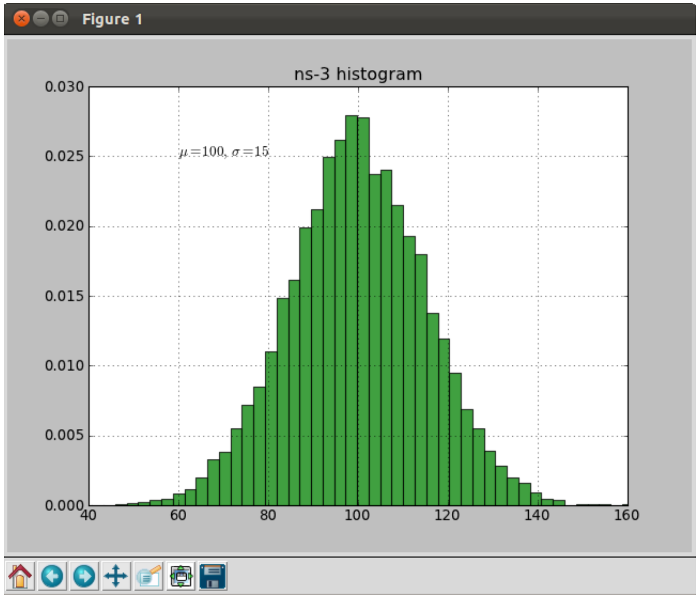
- The Simulator class holds a scheduler, and provides the API to schedule events, start, stop, and cleanup memory
- Several scheduler data structures (calendar, heap, list, map) are possible
- A "RealTime" simulation implementation is possible
  - aligns the simulation time to wall-clock time

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

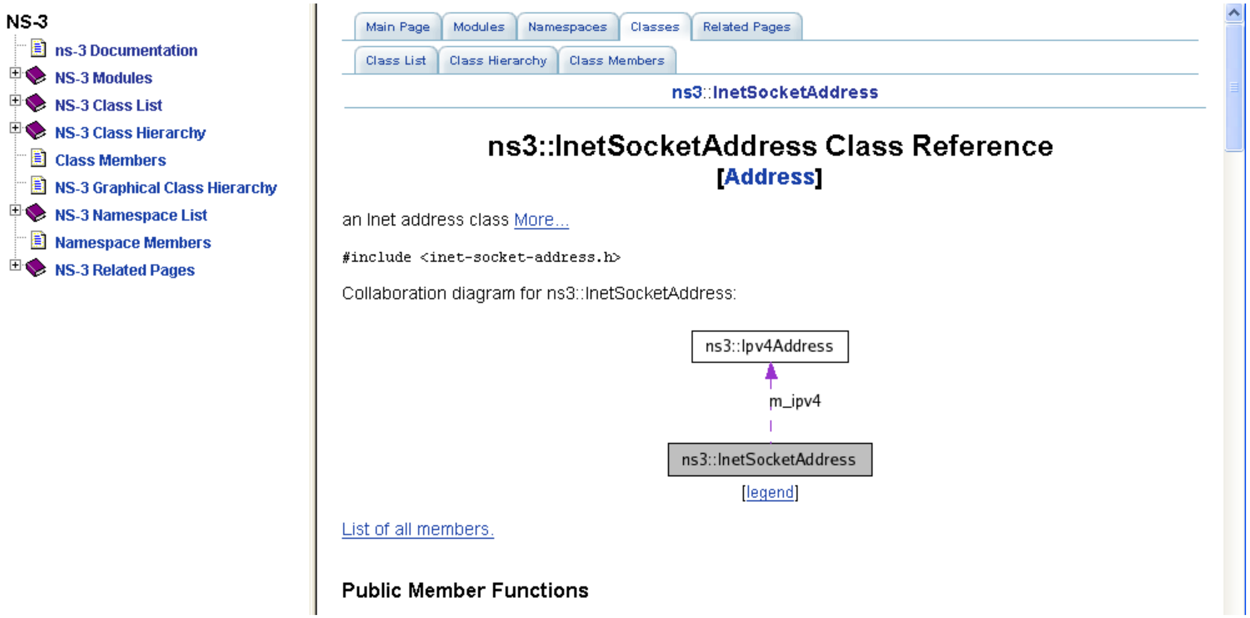
Building without wscript

- 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/

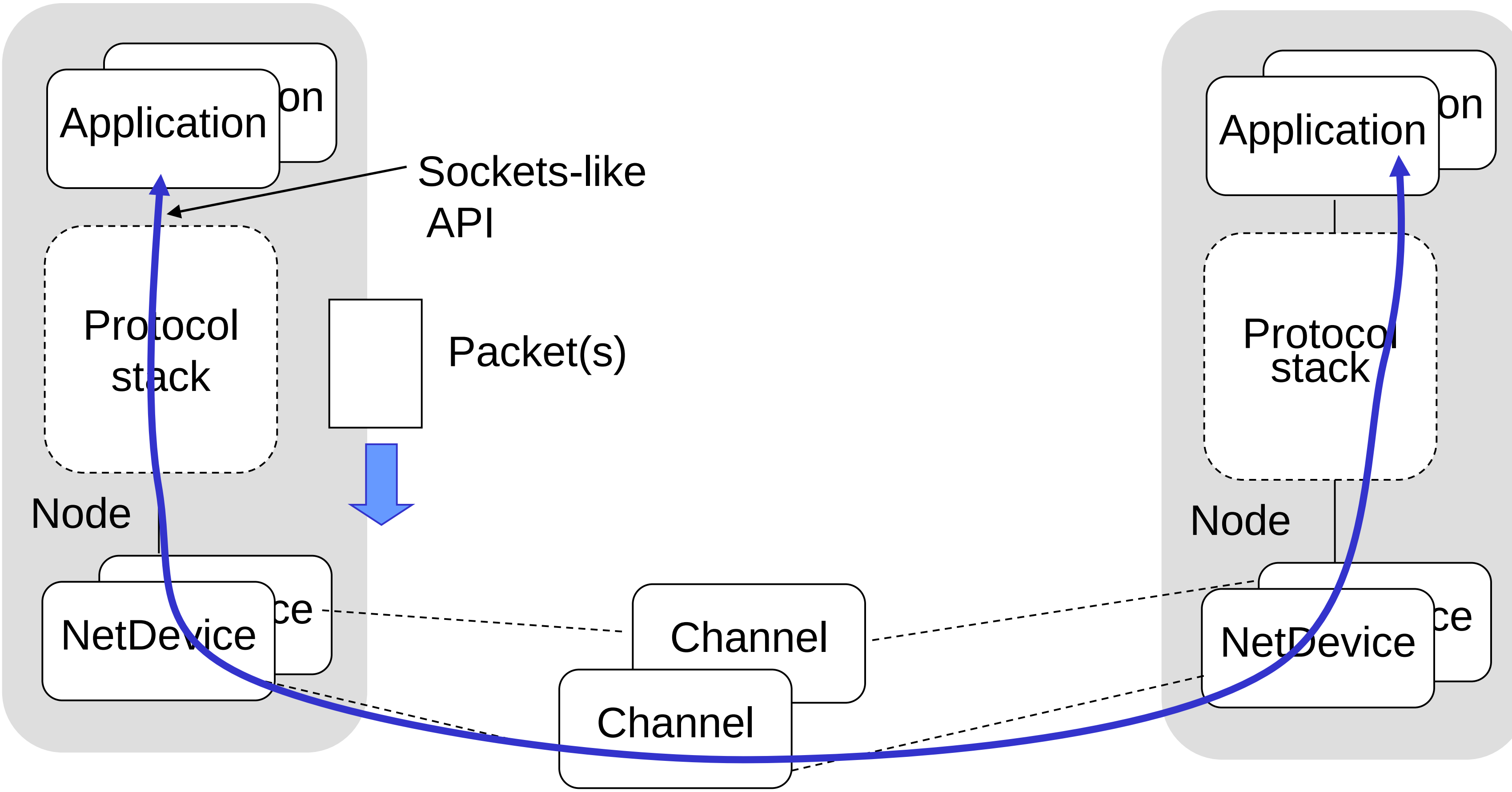


Review of topics covered

- 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



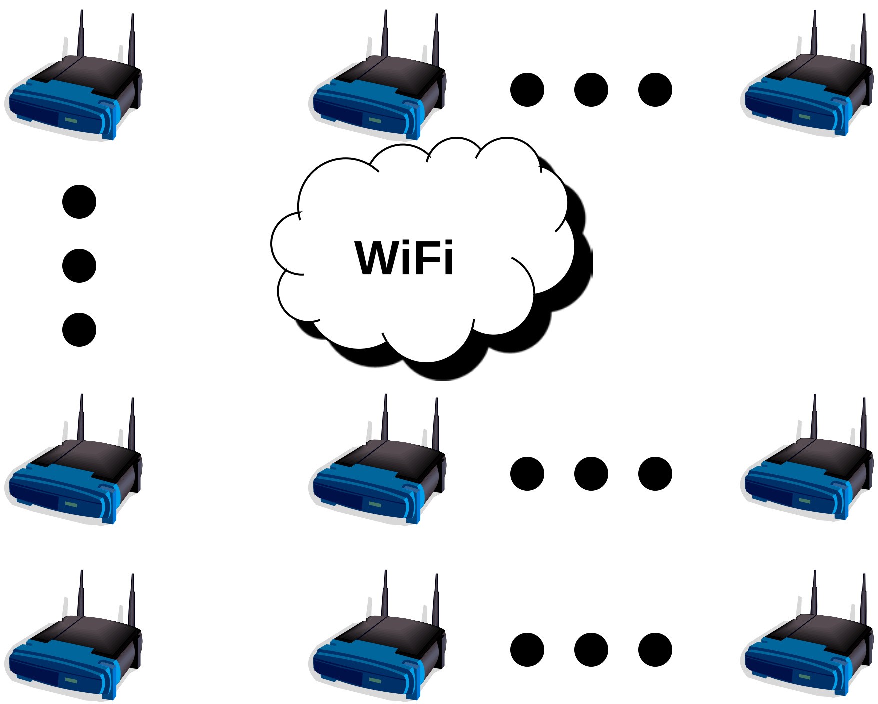
Example program

- `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

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

Sink (node 0) by default

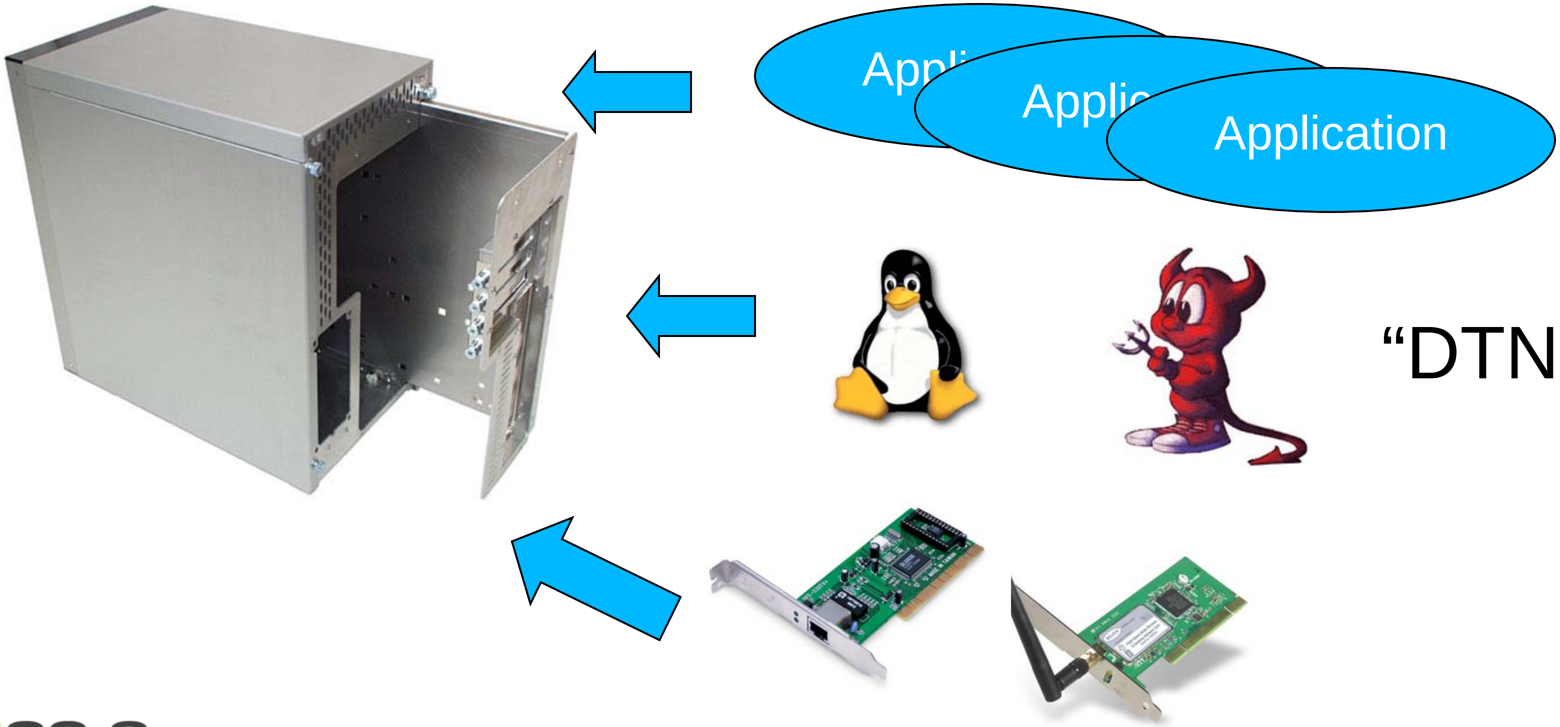
Fundamentals

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

Nodes contain Applications, “stacks”, and NetDevices

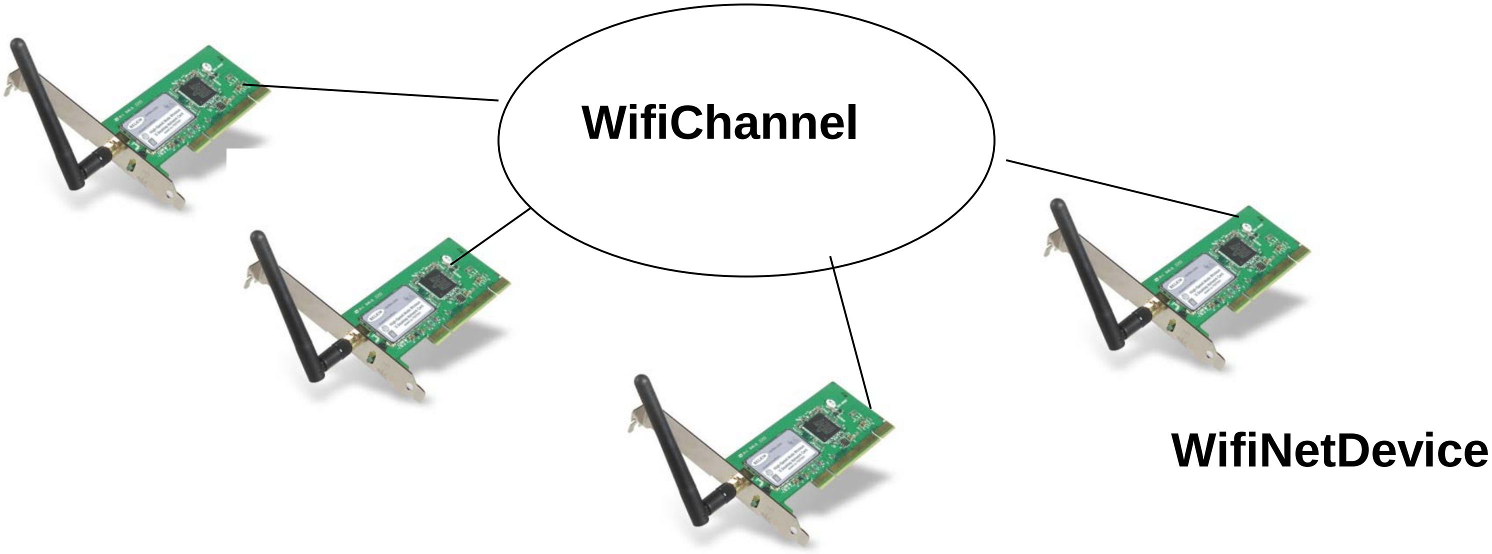
Node basics

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

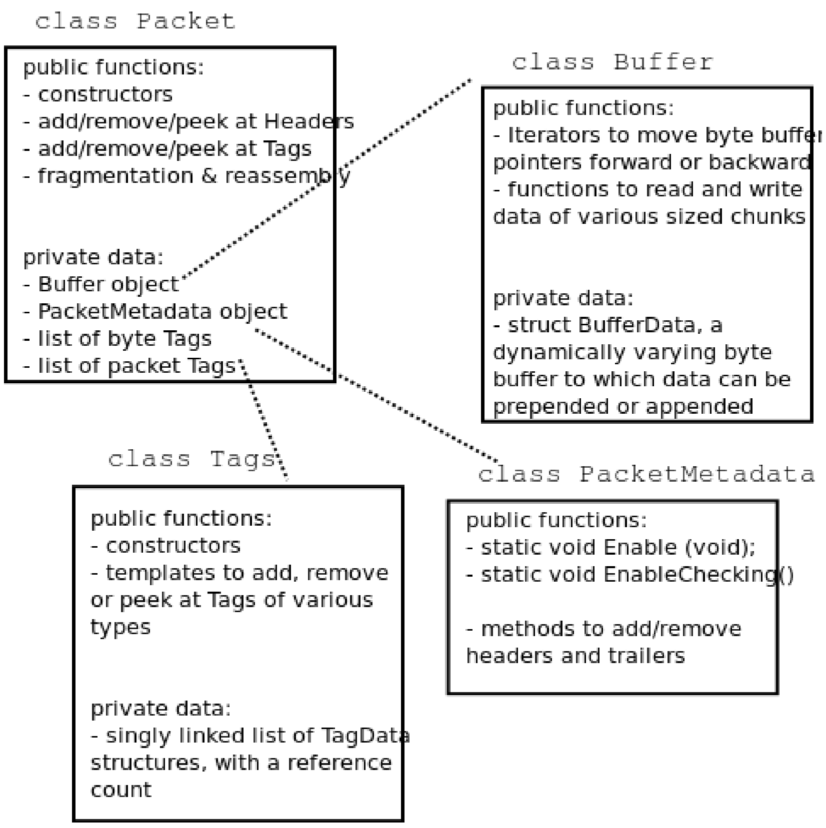
- Devices
  - WiFi, WiMAX, CSMA, Point-to-point, Bridge
- Error models and queues
- Applications
  - echo servers, traffic generator
- Mobility models
- Packet routing
  - OLSR, AODV, DSR, DSDV, Static, Nix-Vector, Global (link state)

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

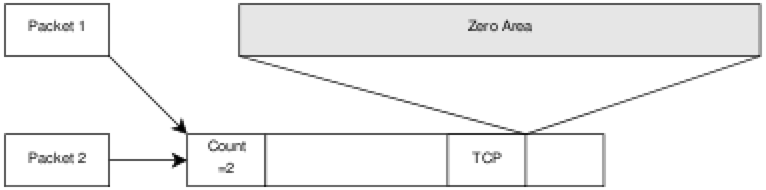


Figure 3.8: The TCP and the IP stacks hold references to a shared buffer.

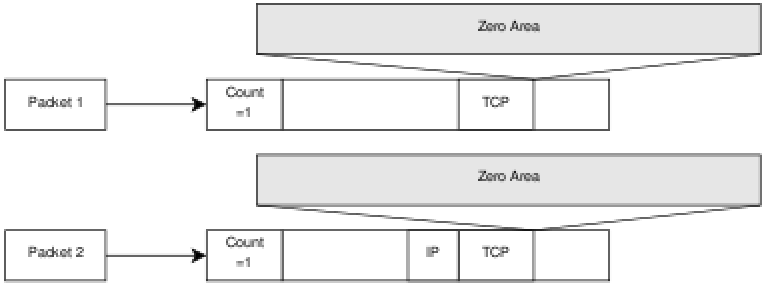


Figure 3.9: The IP stack inserts the IP header, triggers an un-share operation, completes the insertion.

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”

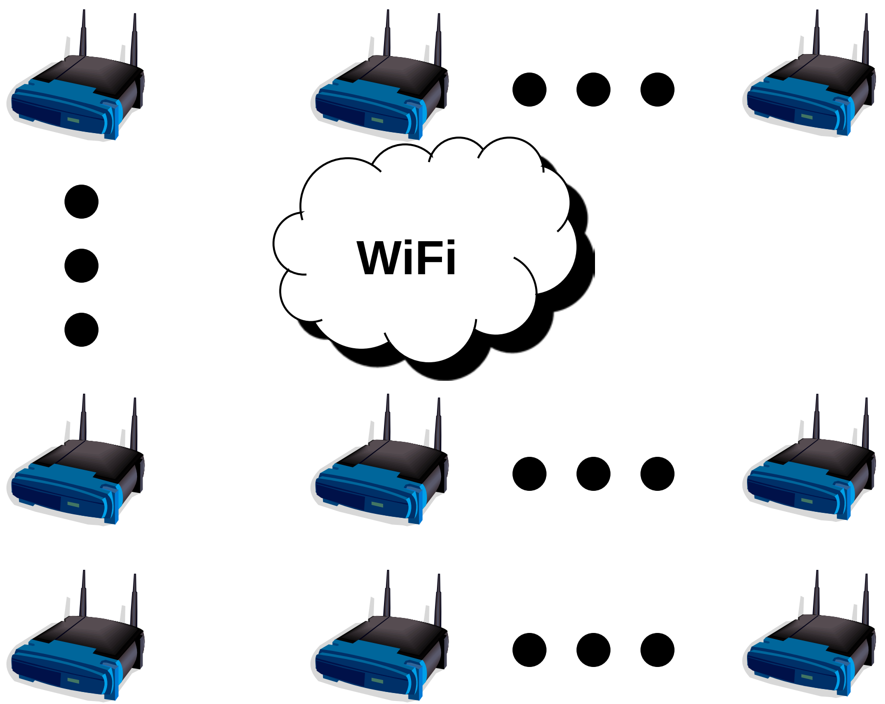
Helper Objects

- 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

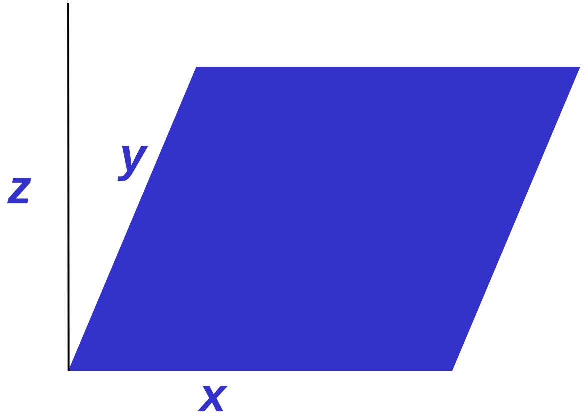
Installation onto containers

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

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

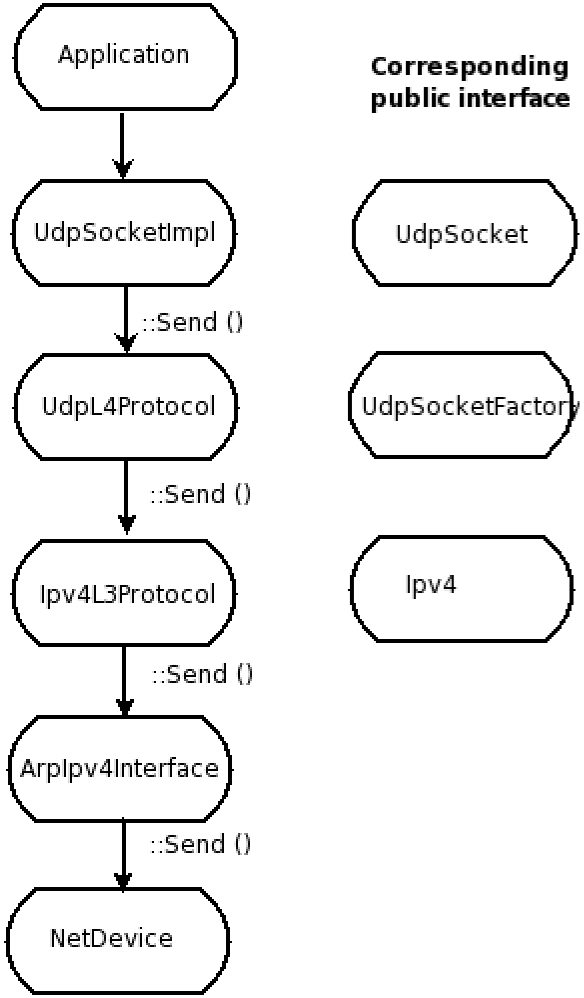
Mobility models in ns-3

- 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

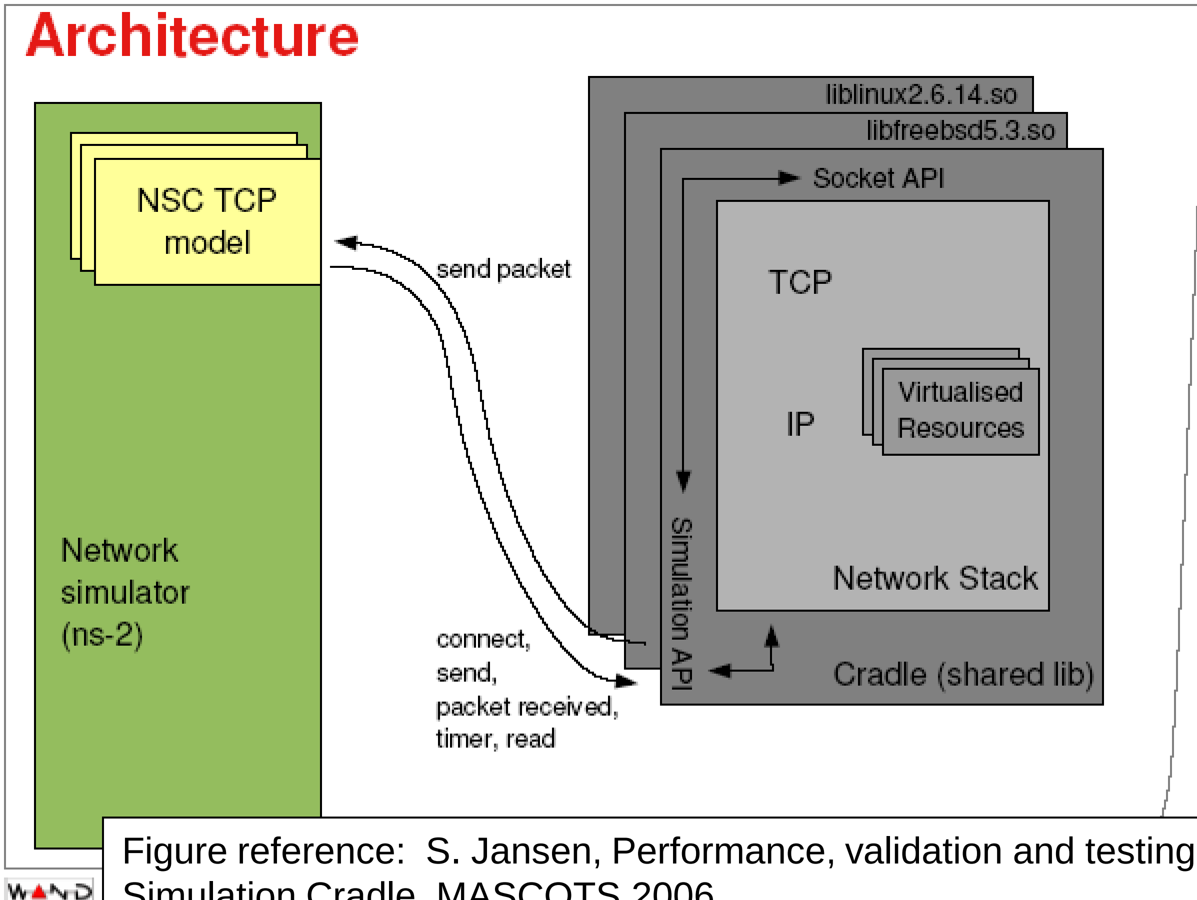
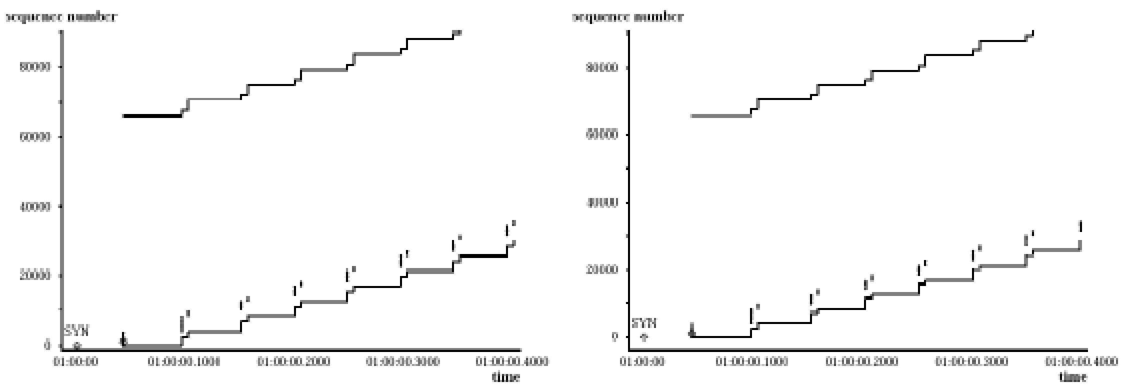


Figure reference: S. Jansen, Performance, validation and testing with the Network Simulation Cradle. MASCOTS 2006.

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

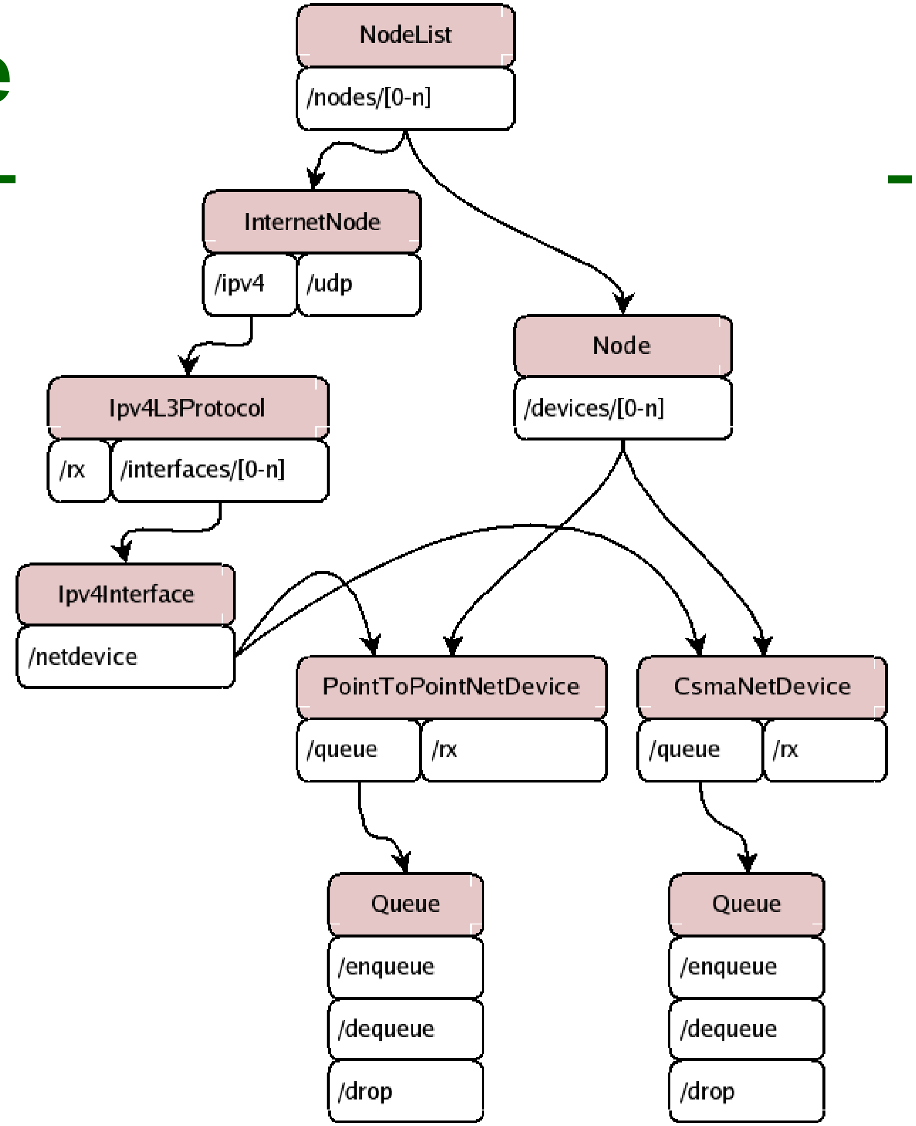
- The traditional C++ way:
  - export attributes as part of a class's public API
  - walk pointer chains (and iterators, when needed) to find what you need
  - use static variables for defaults
- The attribute system provides a more convenient API to the user to do these things

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"));
```

Attribute — Value

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/Ph
  y/TxGain”, DoubleValue(1.0));
```

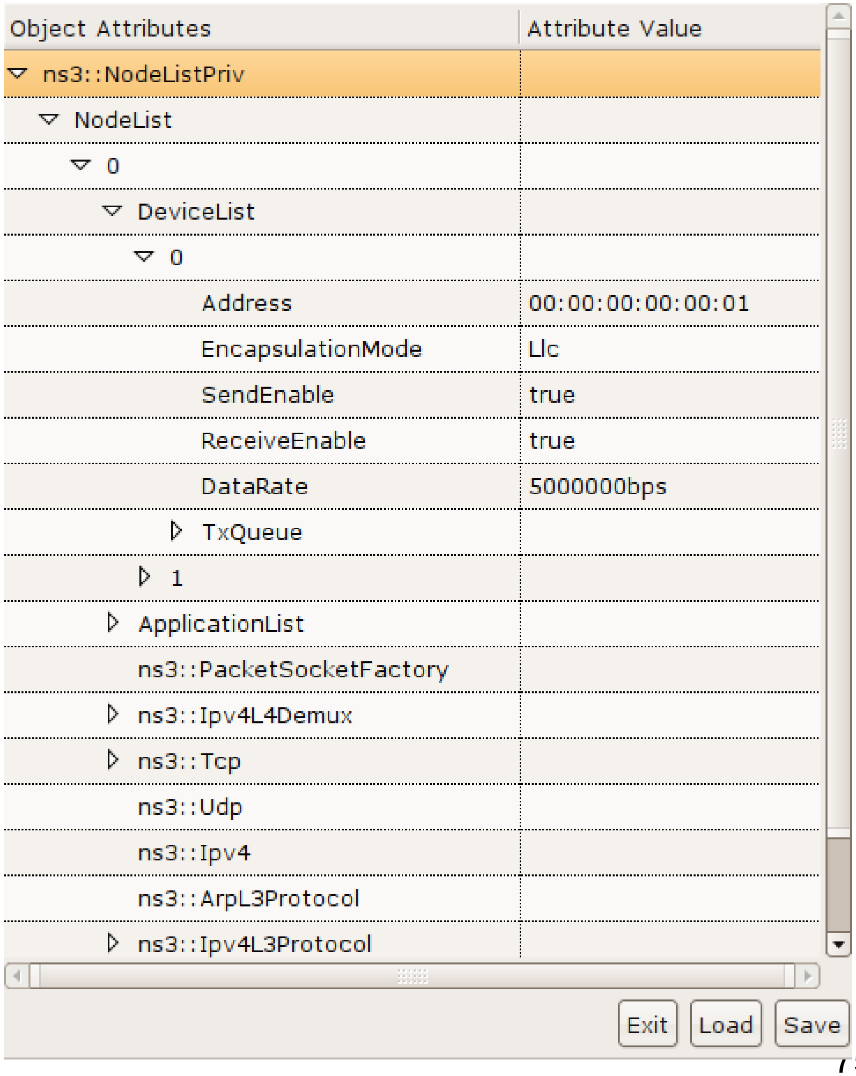
```
DoubleValue d; nodePtr->GetAttribute (
  “/NodeList/5/NetDevice/3/Phy/TxGain”, v);
```

- 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

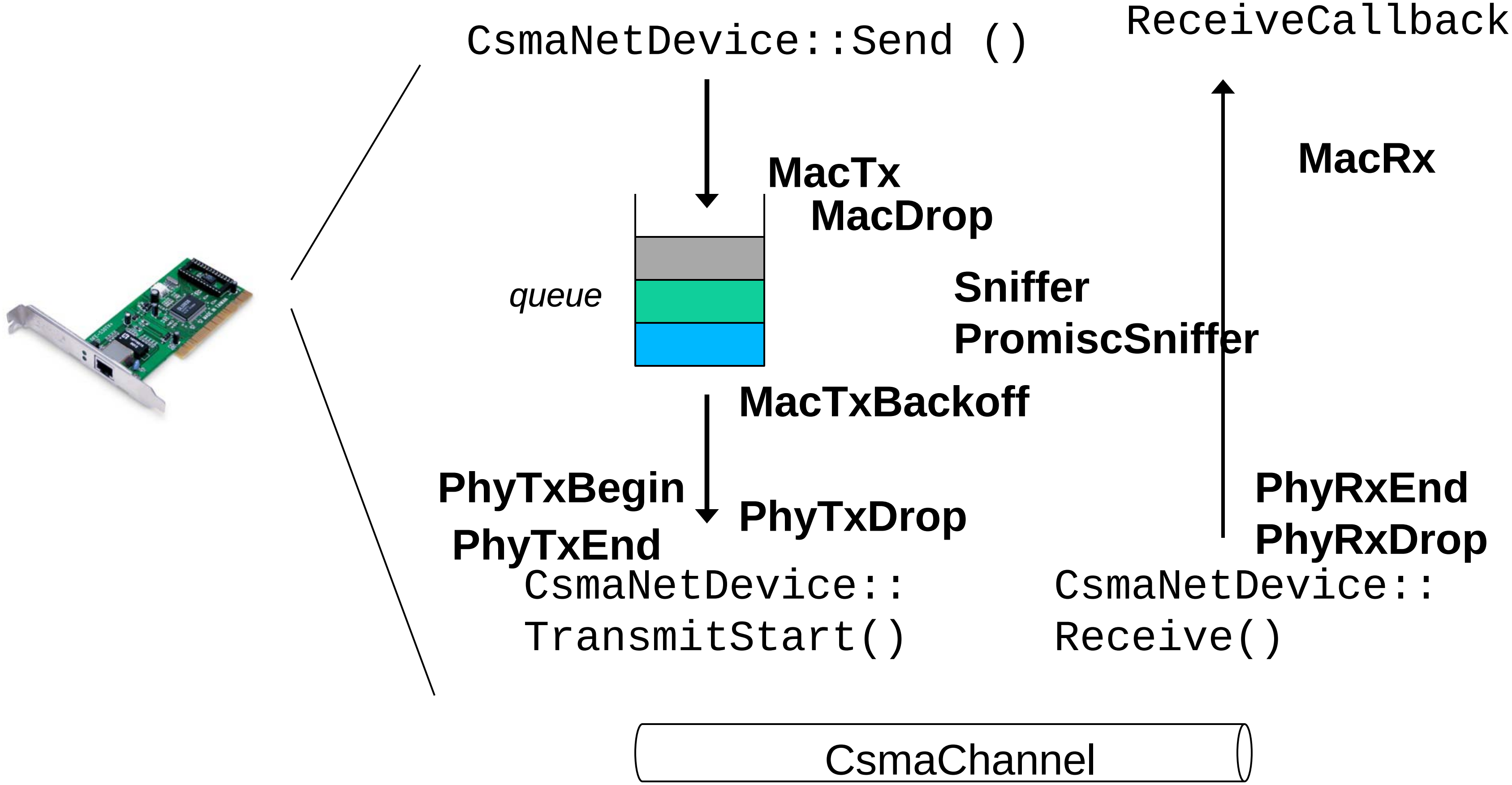
TracedValue → `Config::Connect ("/path/to/traced/value", callback1);`

TraceSource → `Config::Connect ("/path/to/trace/source", callback2);`

TraceSource *unattached*

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

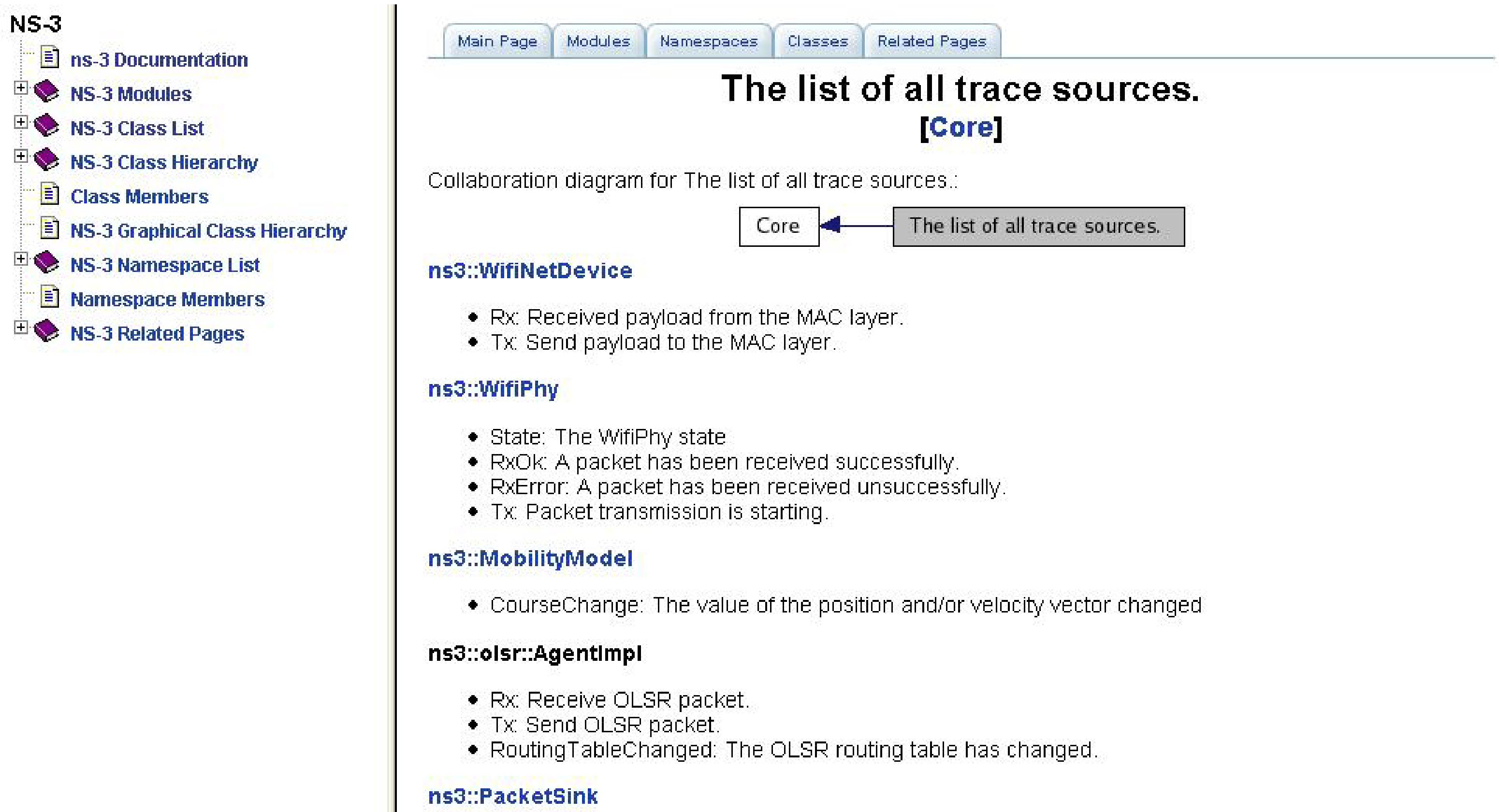
```
pointToPoint.EnablePcapAll ("third");
phy.EnablePcap ("third", apDevices.Get (0));
csma.EnablePcap ("third", csmaDevices.Get (0), true);
```

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
   }
```

ns-3 NETWORK SIMULATOR

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

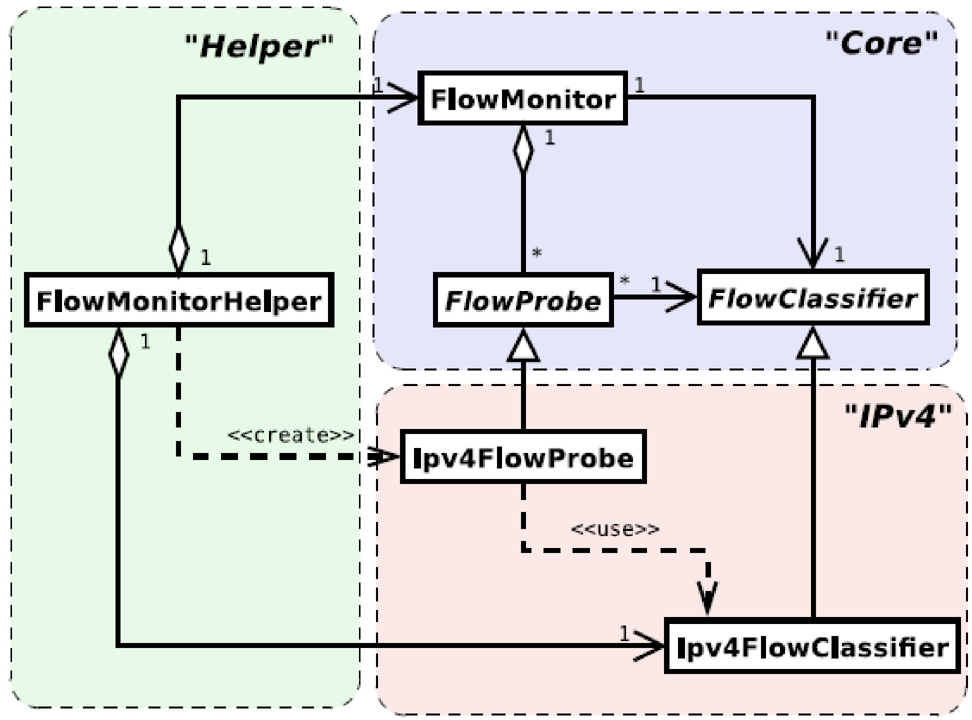


Figure credit: G. Carneiro, P. Fortuna, M. Ricardo, "FlowMonitor-- a network monitoring framework for the Network Simulator ns-3," Proceedings of NSTools 2009.

FlowMonitor statistics

- Statistics gathered

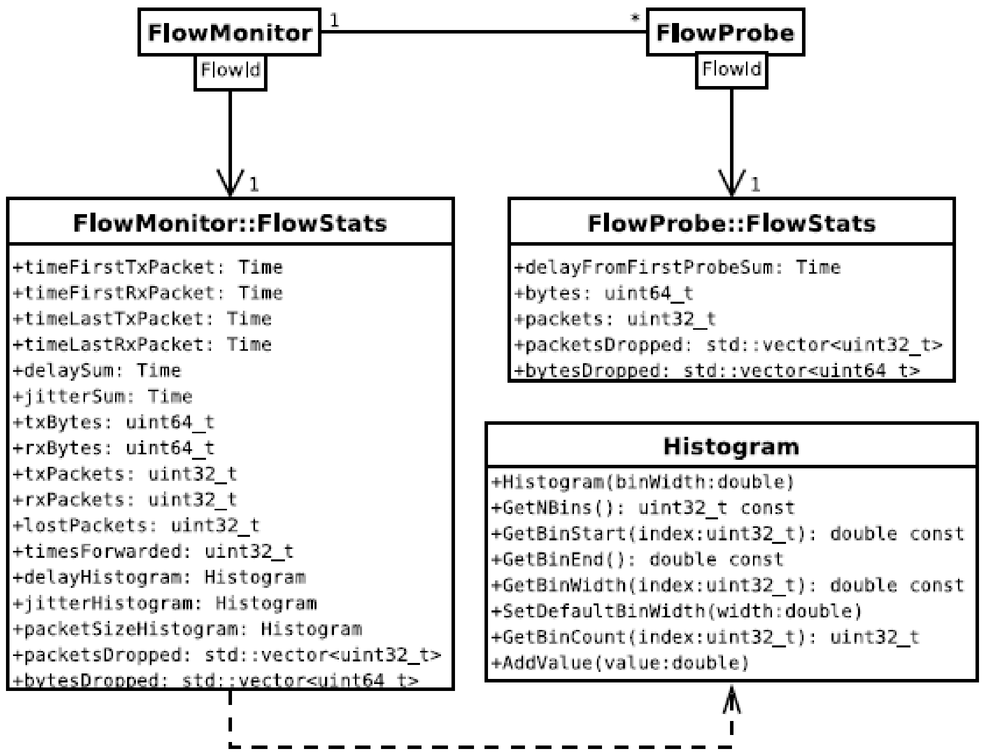


Figure credit: G. Carneiro, P. Fortuna, M. Ricardo, "FlowMonitor-- a network monitoring framework for the Network Simulator ns-3," Proceedings of NSTools 2009.

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

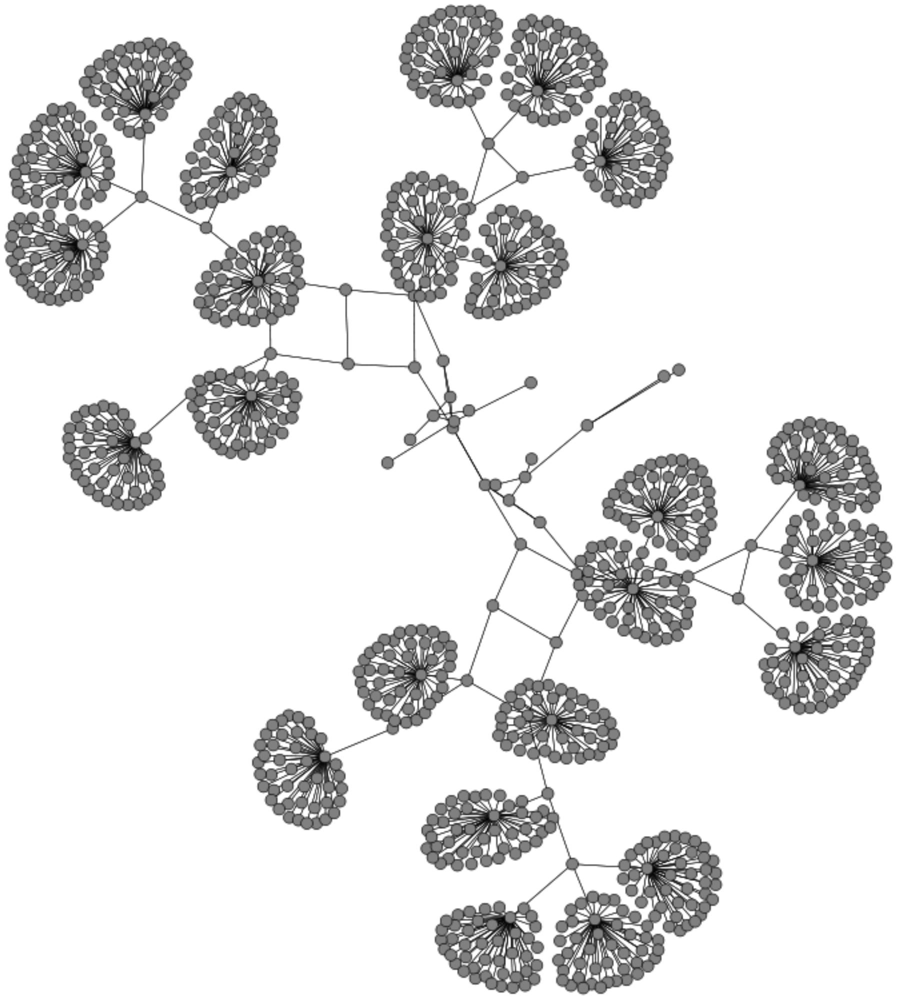
- This program exports statistics to stdout
- Other examples integrate with PyViz

```
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

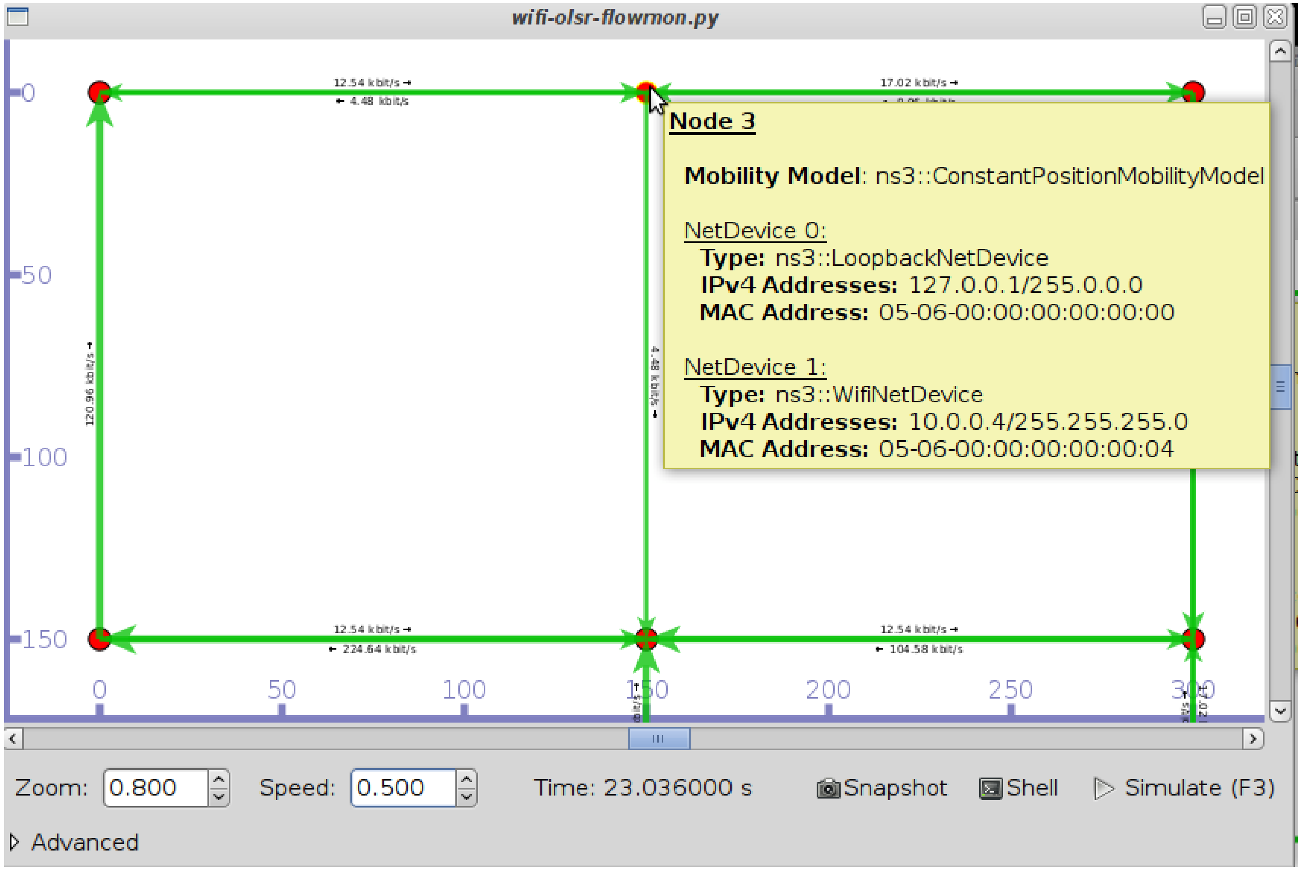
- Developed by Gustavo Carneiro
- Live simulation visualizer (no trace files)
- Useful for debugging
  - mobility model behavior
  - where are packets being dropped?
- Built-in interactive Python console to debug the state of running objects
- Works with Python and C++ programs

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

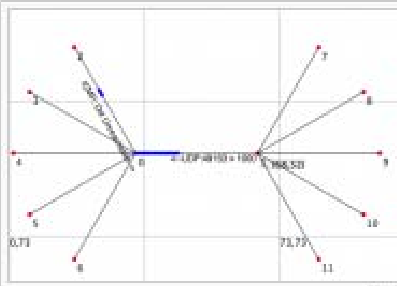
```
--SimulatorImplementationType=
ns3::VisualSimulatorImpl
```

- Alternatively, pass the "--vis" option

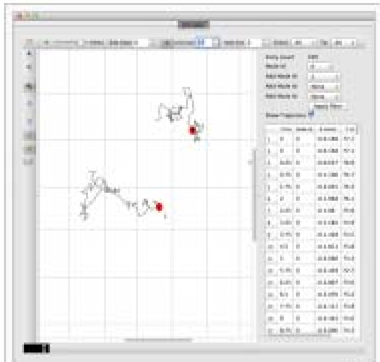
NetAnim

- "NetAnim" by George Riley and John Abraham

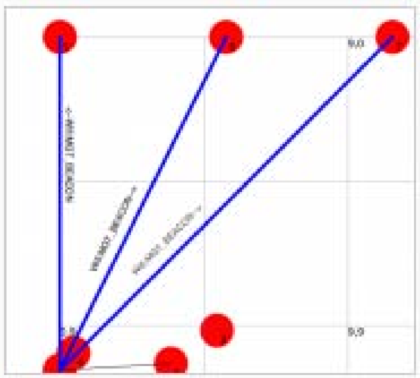
Packet Statistics



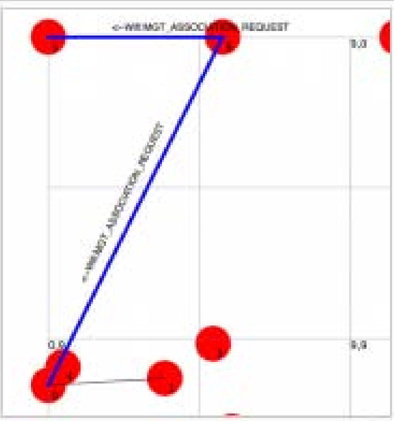
Dumbbell



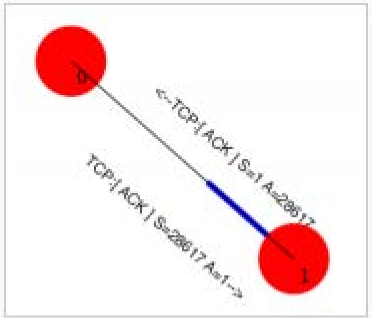
Node Trajectory



Wifi Beacon



Wifi Assoc



TCP flags

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

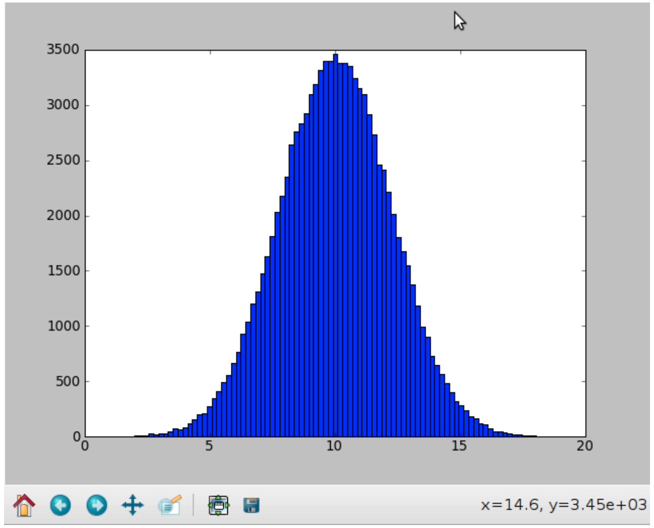
```
    uint32_t pktsRecvd = experiment.Run (wifi, wifiPhy, wifiMac, wifiChannel);
    dataset.Add (rss, pktsRecvd);
  }

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

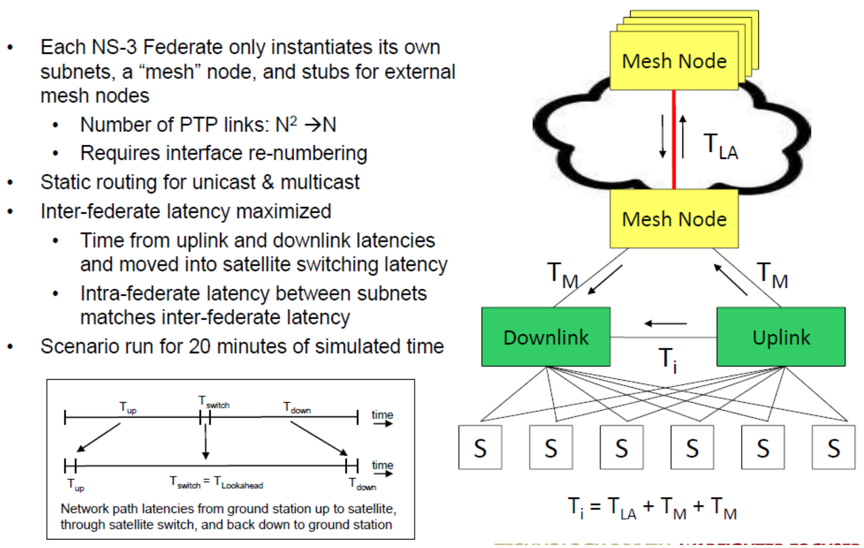
Scaling to multiple machines

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

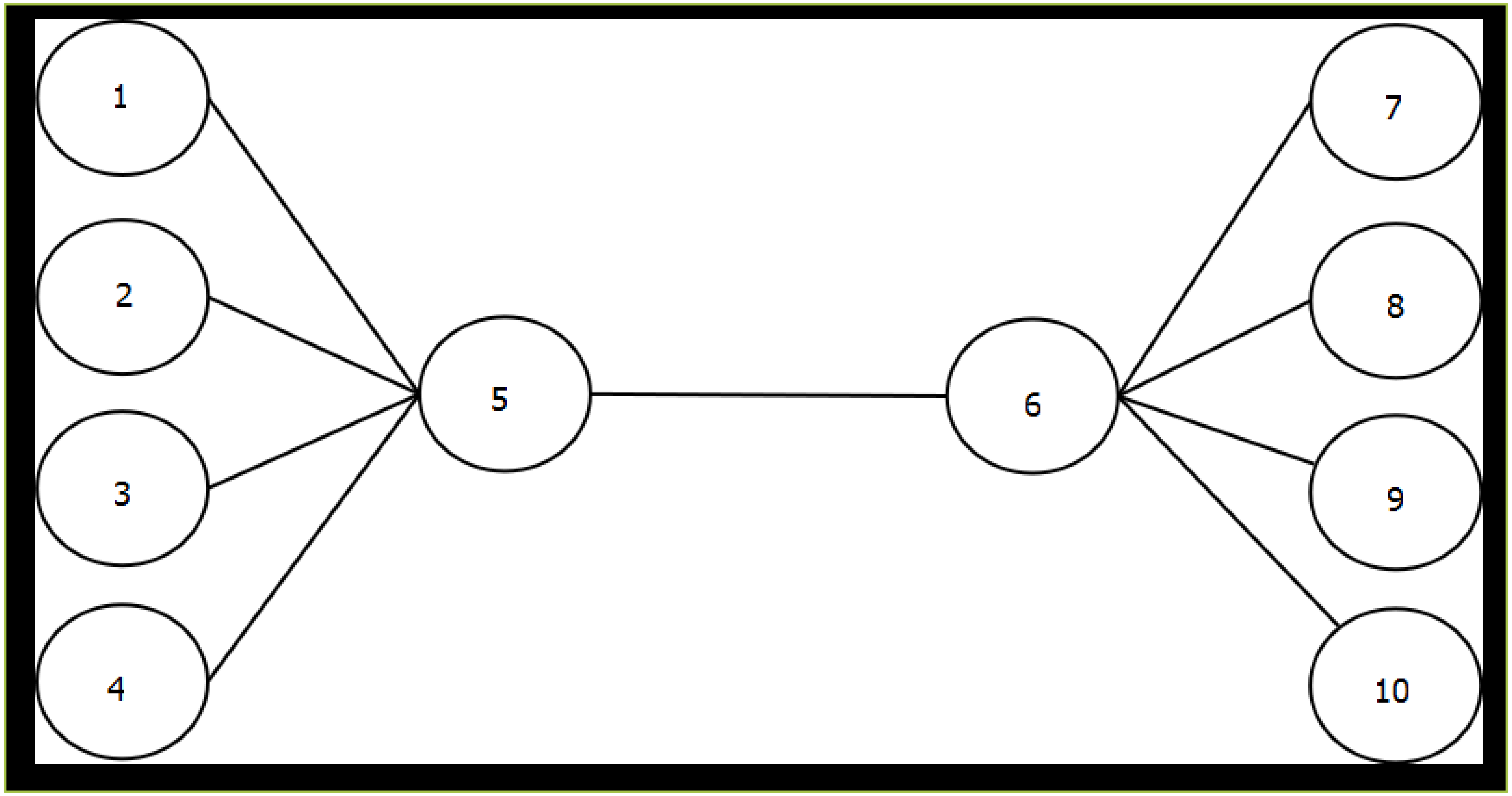
Simulation size record

- 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]

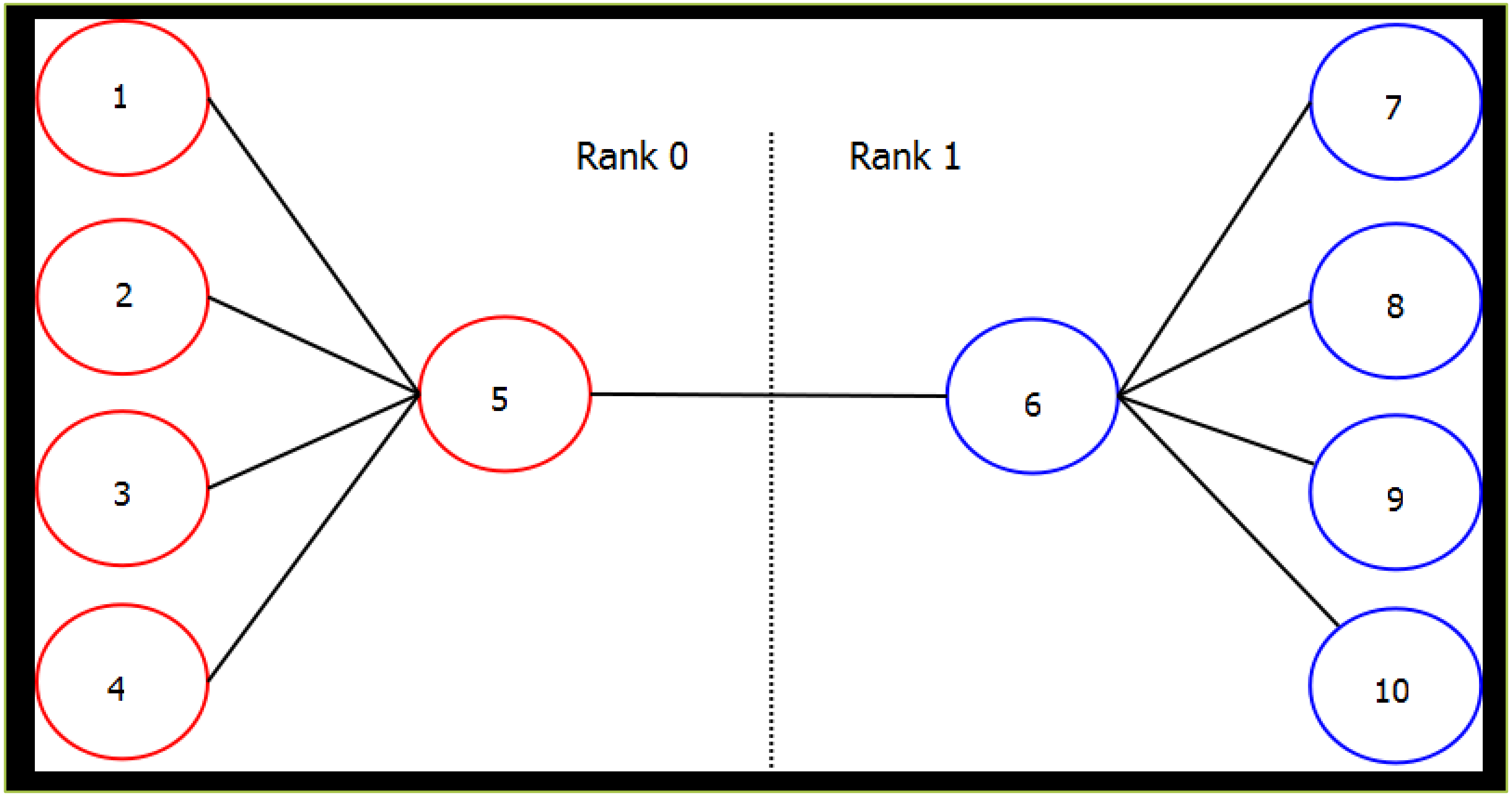


* K. Renard et al, "A Performance and Scalability Evaluation of the NS-3 Distributed Scheduler. Proceedings of WNS3 2012.

Quick and Easy Example



Quick and Easy Example



Implementation Details

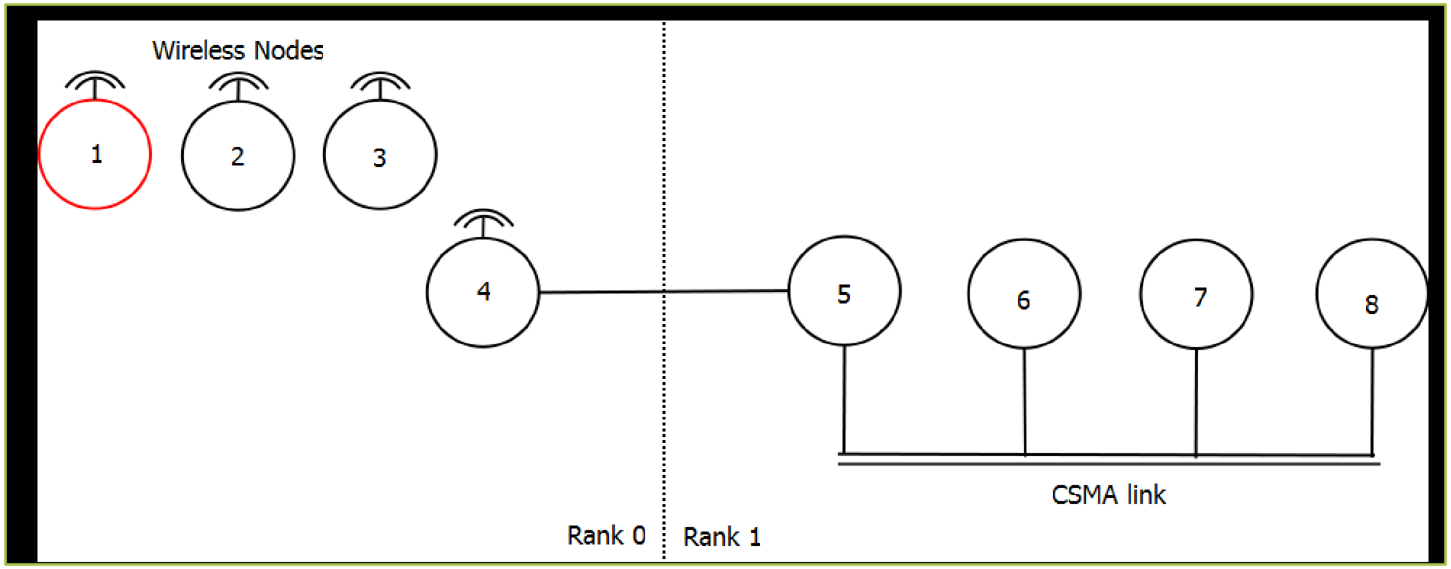
- LP communication
  - Message Passing Interface (MPI) standard
  - Send/Receive time-stamped messages
  - MpiInterface in ns-3
- Synchronization
  - Conservative algorithm using lookahead
  - DistributedSimulator in ns-3

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.)

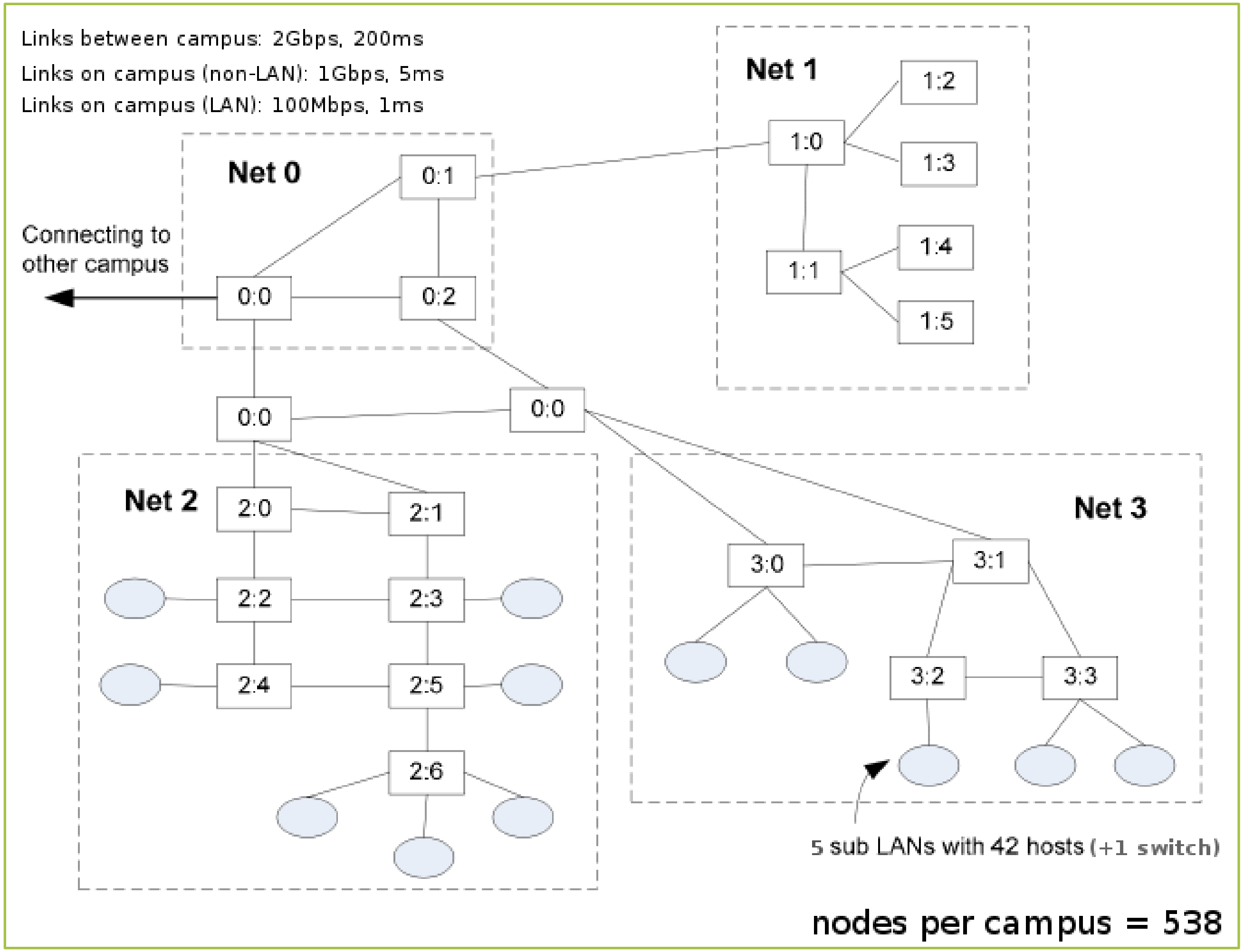
- Distributing the topology
  - All nodes created on all LPs, regardless of rank
  - Applications are only installed on LPs with target node



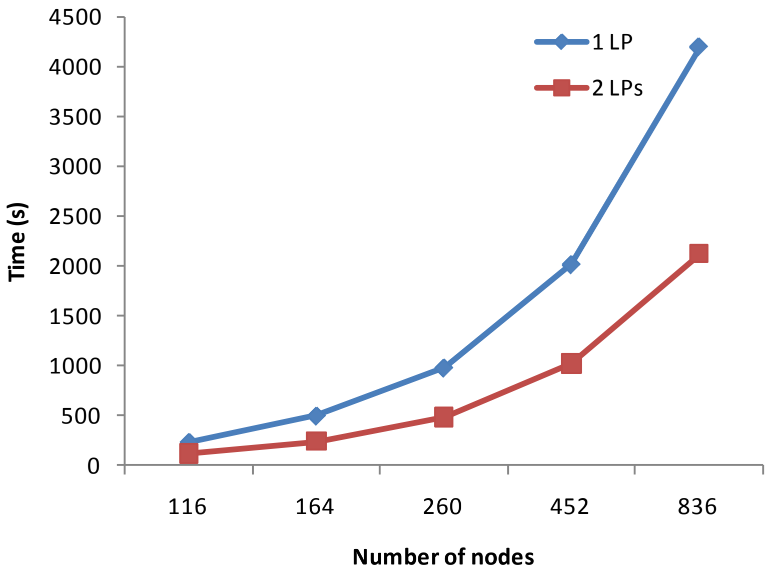
Performance Test

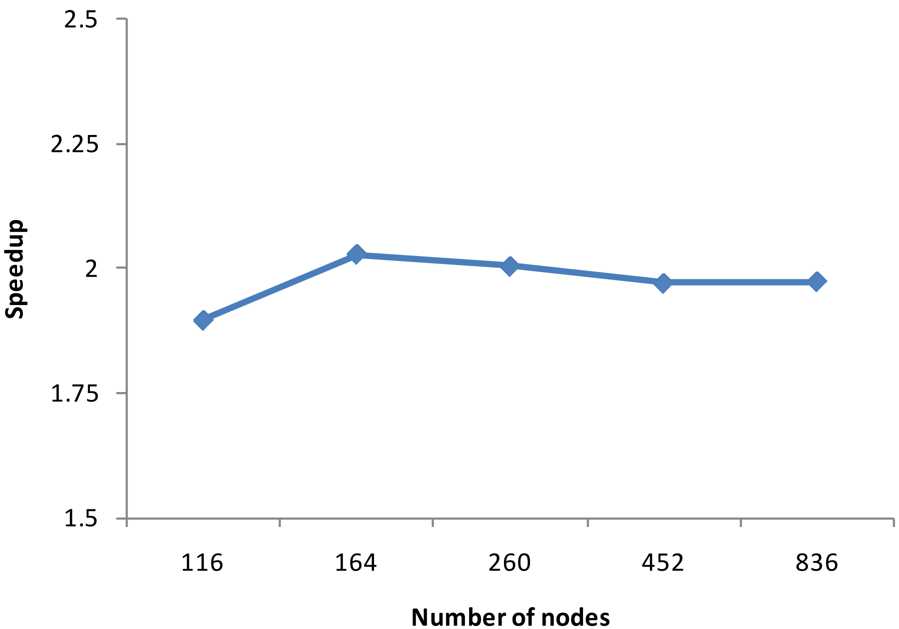
- DARPA NMS campus network simulation
  - Allows creation of very large topologies
  - Any number of campus networks are created and connected together
  - Different campus networks can be placed on different LPs
  - Tested with 2 CNs, 4 CNs, and 6 CNs

Campus Network Topology



2 Campus Networks





Summary

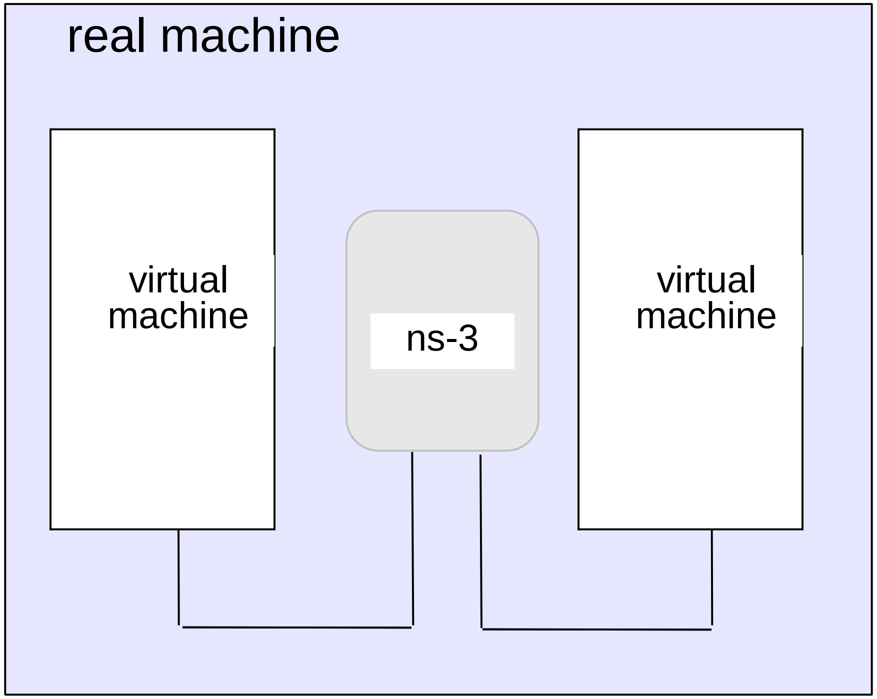
- Distributed simulation in ns-3 allows a user to run a single simulation in parallel on multiple processors
- By assigning a different rank to nodes and connecting these nodes with point-to-point links, simulator boundaries are created
- Simulator boundaries divide LPs, and each LP can be executed by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

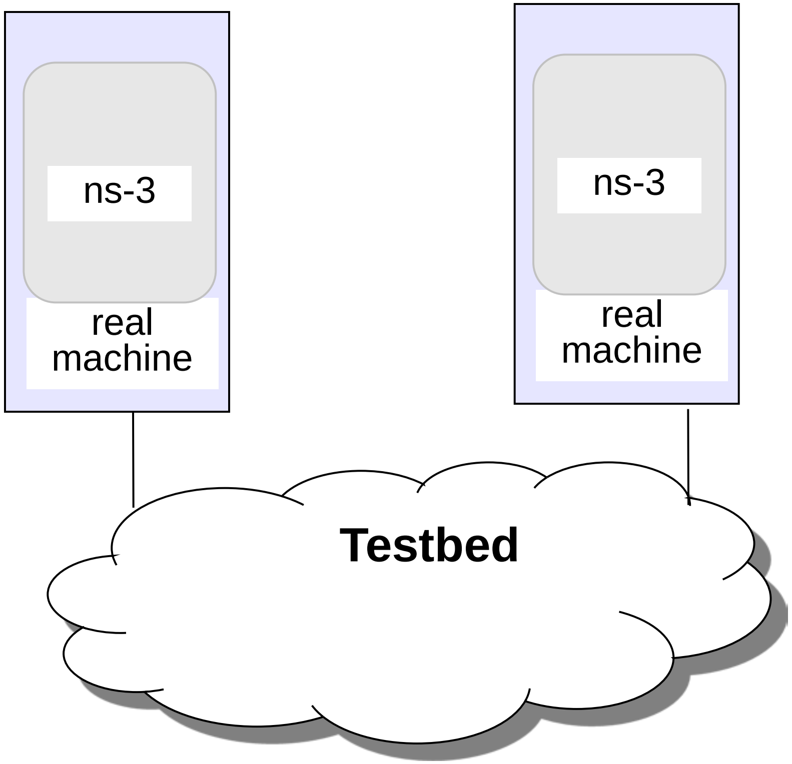
emulation and testbeds

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



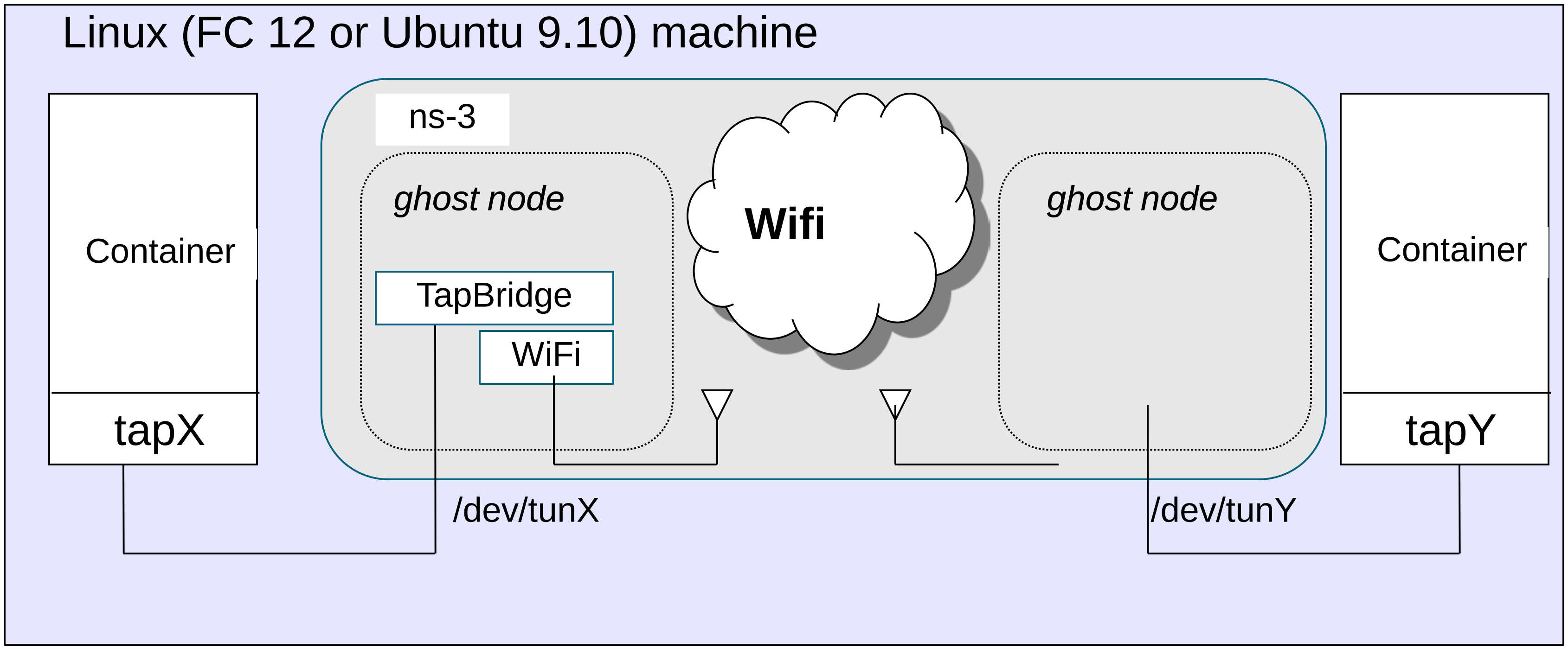


1) ns-3 interconnects real or virtual machines

2) testbeds interconnect ns-3 stacks

Various hybrids of the above are possible

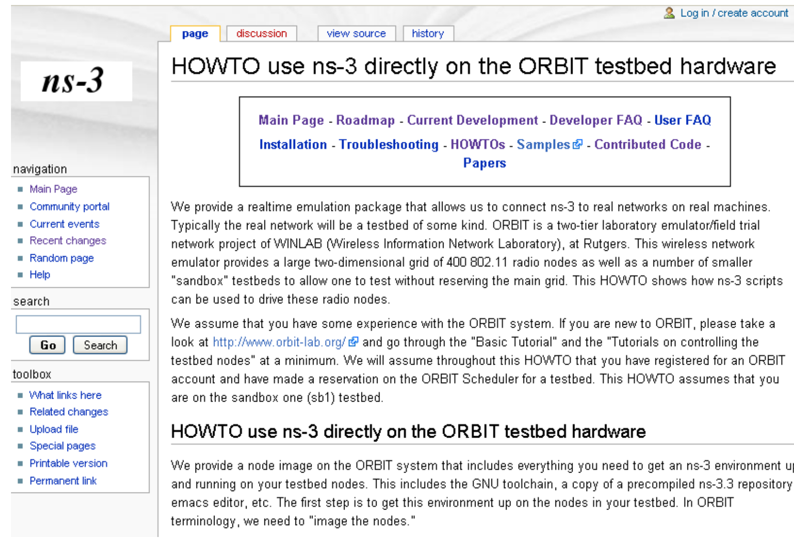
“Tap” mode: netns and ns-3 integration



Tap device pushed into namespaces; no bridging needed

Example: ORBIT and ns-3

- Support for use of Rutgers WINLAB ORBIT radio grid



Log in / create account

page | discussion | view source | history

ns-3

navigation

- Main Page
- Community portal
- Current events
- Recent changes
- Random page
- Help

search

Go | Search

toolbox

- What links here
- Related changes
- Upload file
- Special pages
- Printable version
- Permanent link

HOWTO use ns-3 directly on the ORBIT testbed hardware

Main Page - Roadmap - Current Development - Developer FAQ - User FAQ
Installation - Troubleshooting - HOWTOs - Samples - Contributed Code - Papers

We provide a realtime emulation package that allows us to connect ns-3 to real networks on real machines. Typically the real network will be a testbed of some kind. ORBIT is a two-tier laboratory emulator/field trial network project of WINLAB (Wireless Information Network Laboratory), at Rutgers. This wireless network emulator provides a large two-dimensional grid of 400 802.11 radio nodes as well as a number of smaller "sandbox" testbeds to allow one to test without reserving the main grid. This HOWTO shows how ns-3 scripts can be used to drive these radio nodes.

We assume that you have some experience with the ORBIT system. If you are new to ORBIT, please take a look at http://www.orbit-lab.org/ and go through the "Basic Tutorial" and the "Tutorials on controlling the testbed nodes" at a minimum. We will assume throughout this HOWTO that you have registered for an ORBIT account and have made a reservation on the ORBIT Scheduler for a testbed. This HOWTO assumes that you are on the sandbox one (sb1) testbed.

HOWTO use ns-3 directly on the ORBIT testbed hardware

We provide a node image on the ORBIT system that includes everything you need to get an ns-3 environment up and running on your testbed nodes. This includes the GNU toolchain, a copy of a precompiled ns-3.3 repository, emacs editor, etc. The first step is to get this environment up on the nodes in your testbed. In ORBIT terminology, we need to "image the nodes."

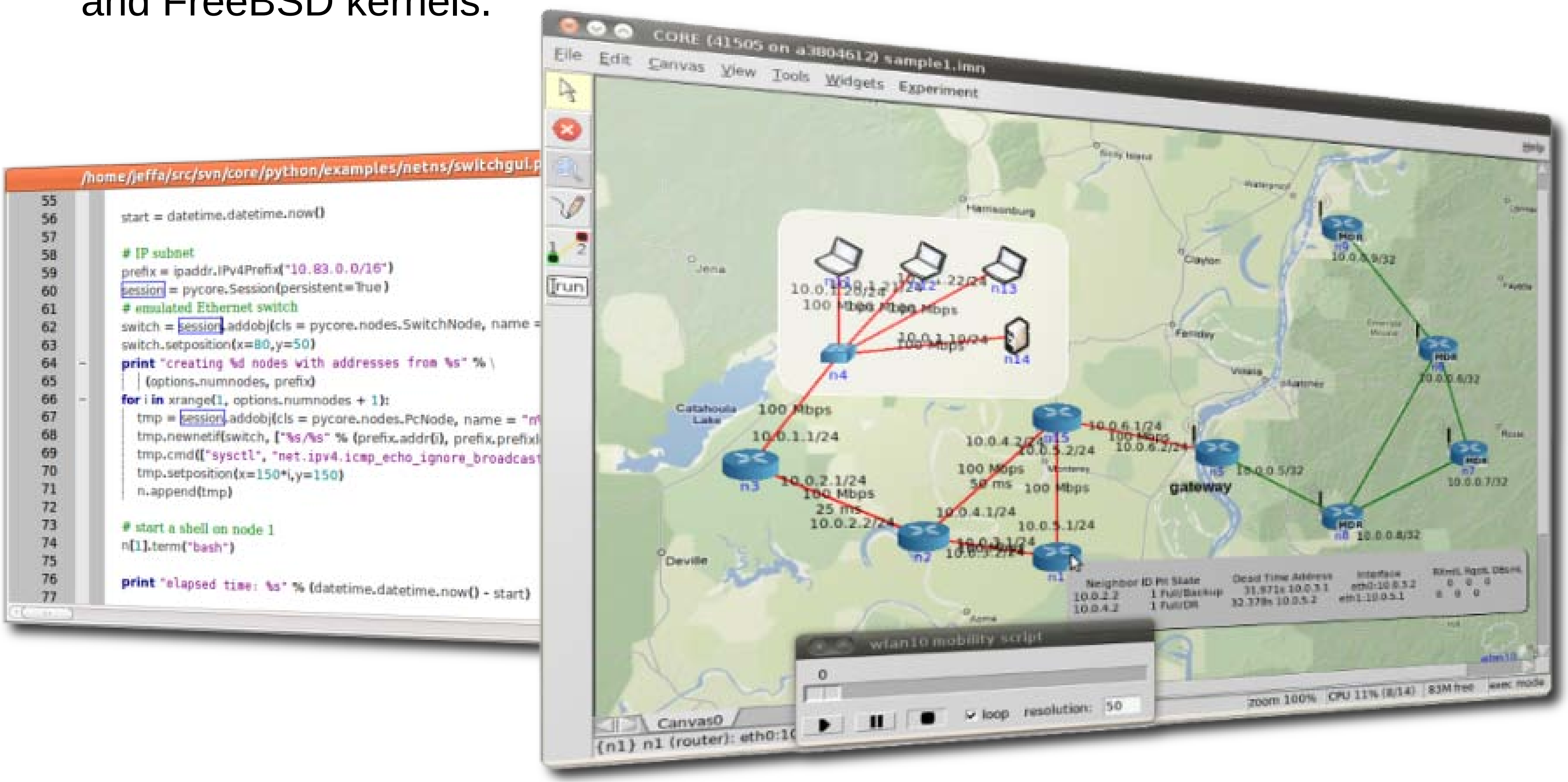
Issues

- 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.

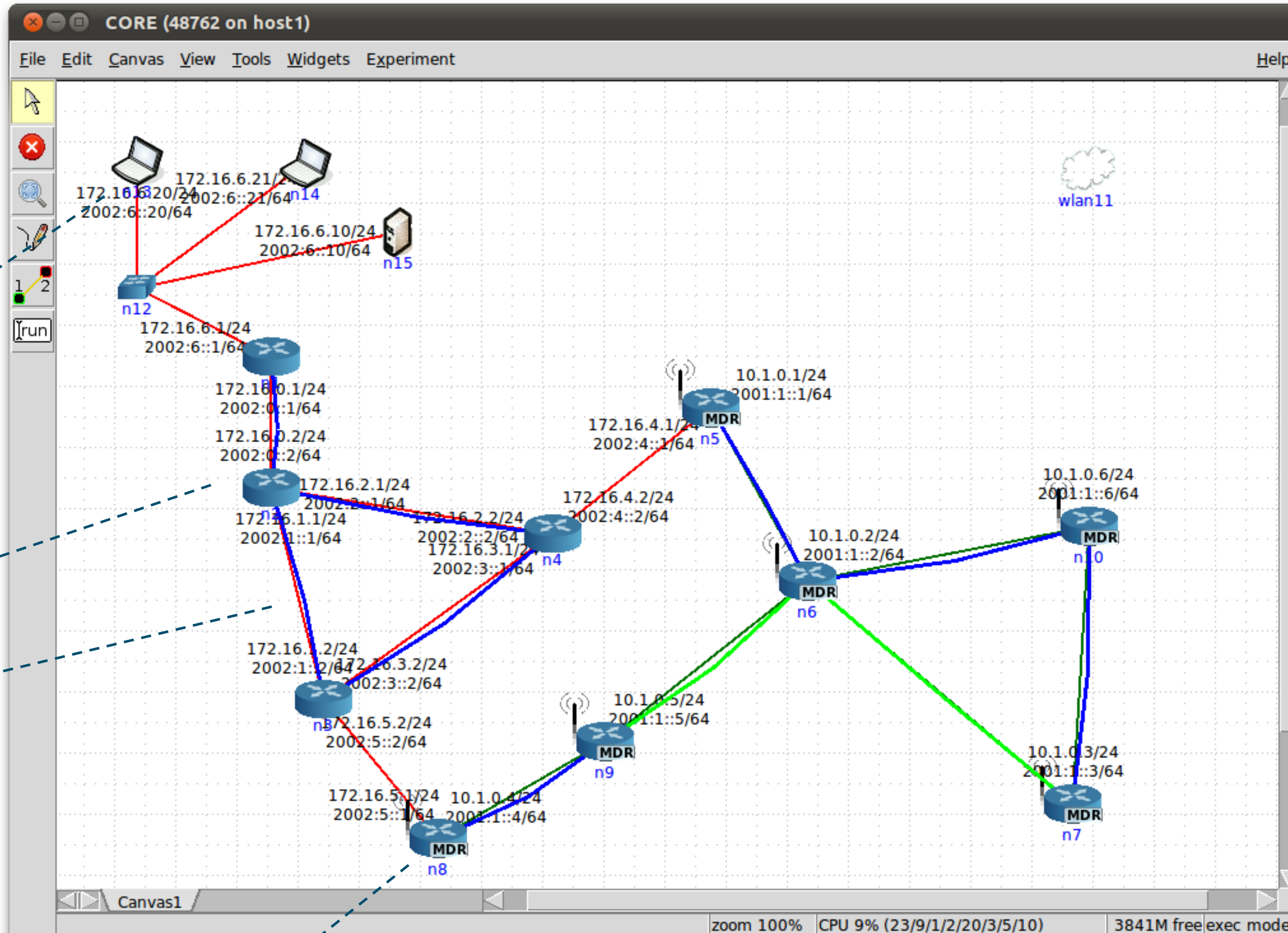


Screenshot

Lightweight VMs Double-click for shell

Wired networks

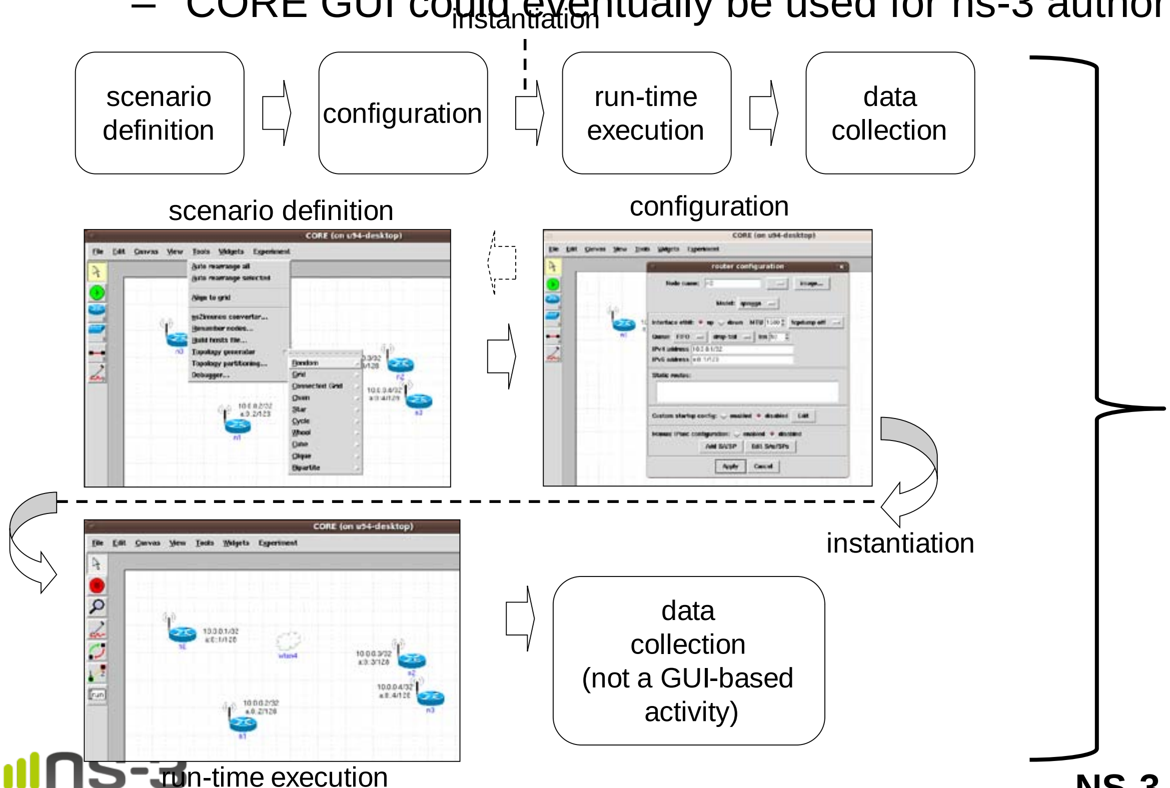
Visualize routing state



Wireless networks

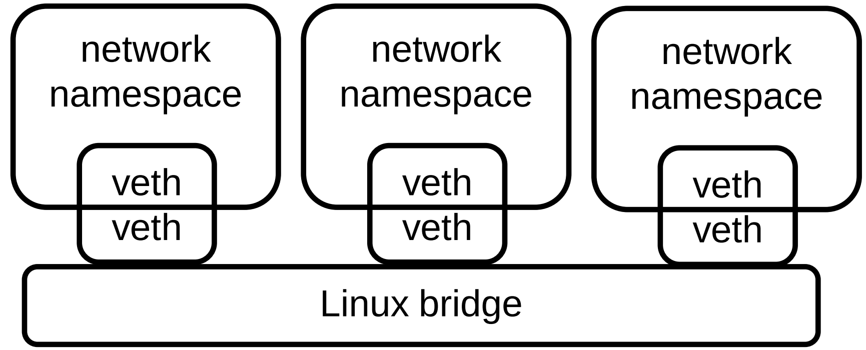
Technical Goals

- 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

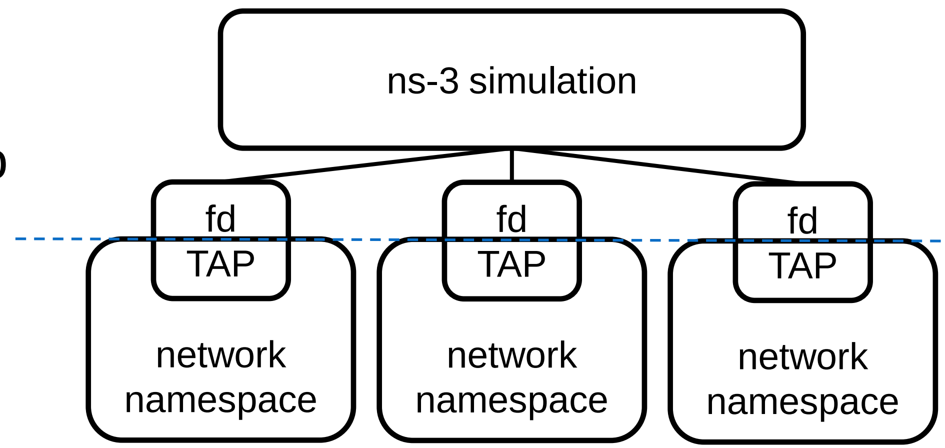


Virtual Interfaces

- 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.



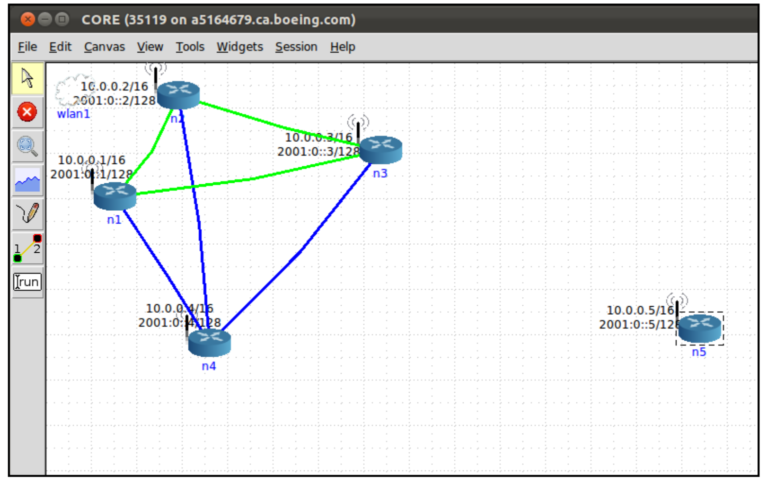
- CORE + ns-3
  - TUN/TAP device installed into a namespace, socket held by simulation.
  - Simulation runs with real-time scheduler.

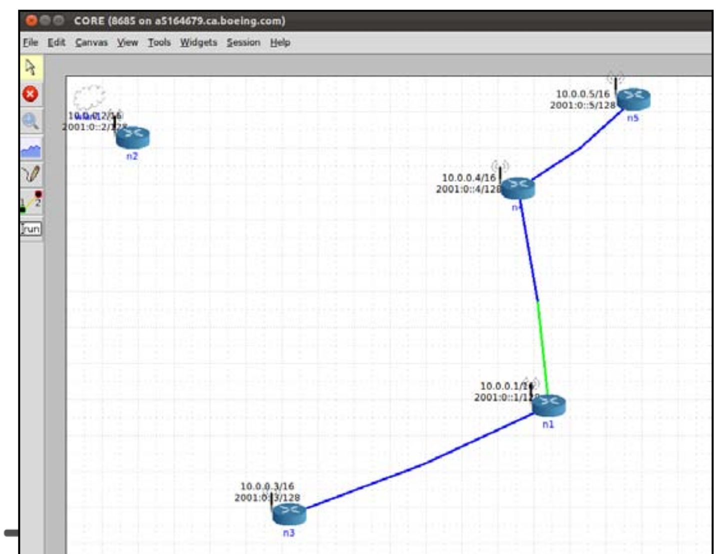


Mobility demonstration

<u>Canvas-based mobility</u>

- ns-3 ConstantPosition MobilityModel
- users can drag nodes around and change topology





<u>ns-3 mobility visualization</u>

- 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

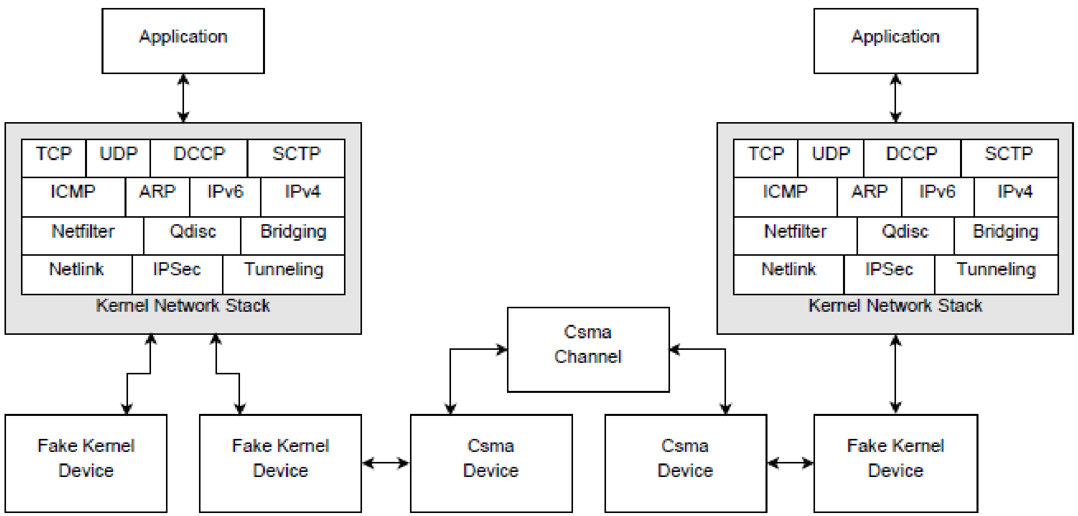


Figure 4.6: The Linux network stack running inside ns-3

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

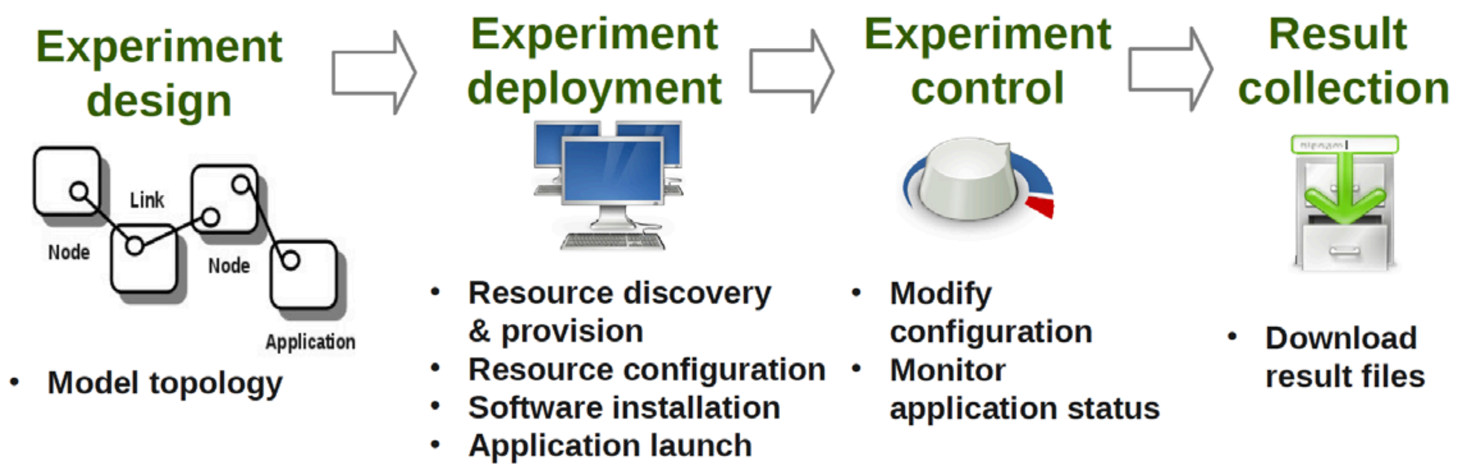


Figure source: Alina Quereilhac, INRIA

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?