NS-3: Network Simulator 3

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Outline

- NS-3 general overview
- NS-3 internal APIs overview
- Short Tutorial

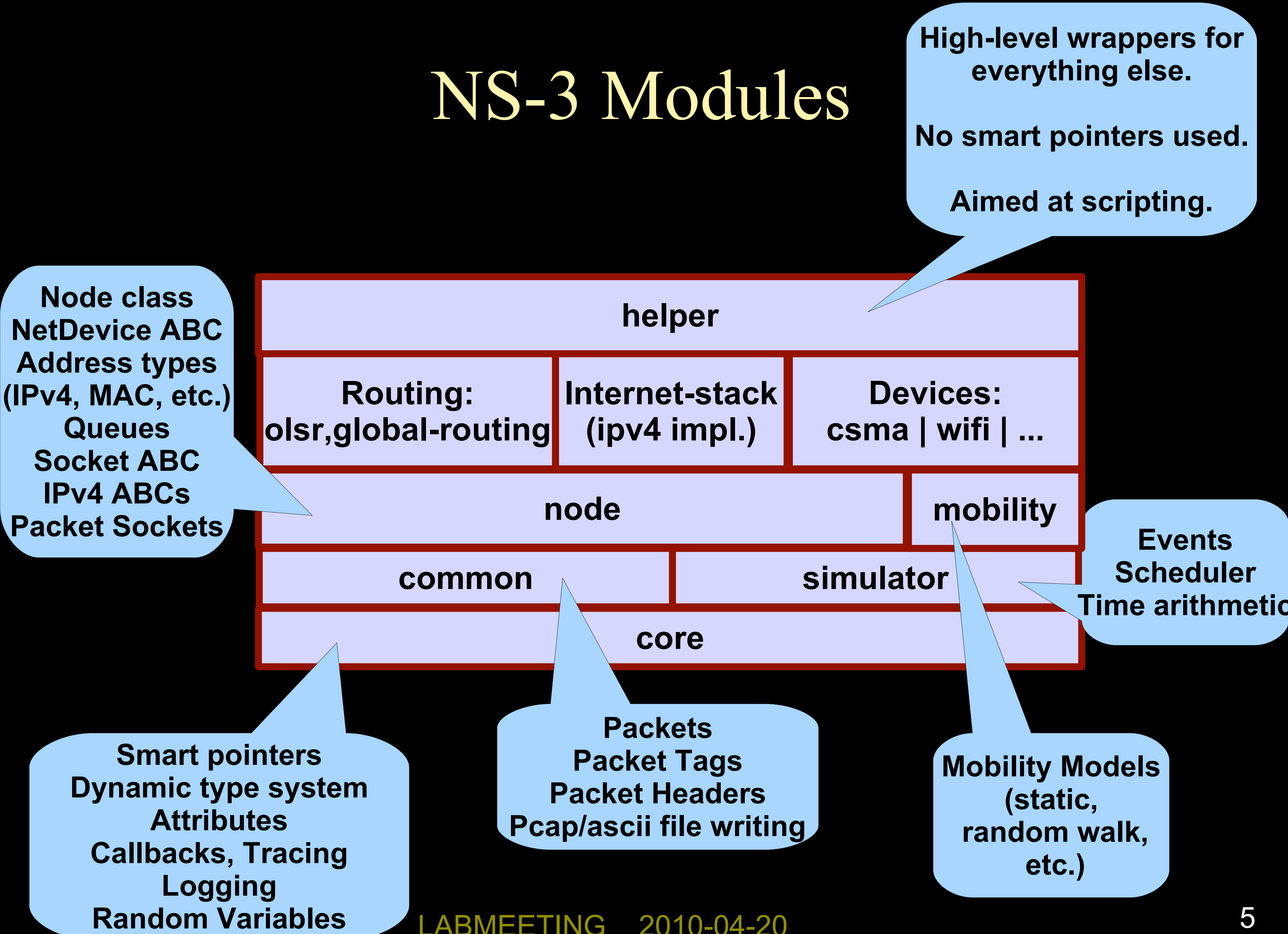
Introduction: NS-2

- The most used simulator for network research
  - "Over 50% of ACM and IEEE network simulation papers from 2000-2004 cite the use of *ns-2*"
- Went unmaintained for a long period of time
- Outdated code design
  - Does not take into account modern programming
    - Smart pointers?
    - Design patterns?
  - Does not scale as well as some alternatives
    - (e.g. GTNetS)
  - Tracing system is difficult to use
    - Need to parse trace files to extract results
    - Trace files end up either
      - Having information researchers do not need, or
      - Missing information
        - It's usual practice to add printf's in the ns-2 code

Introduction: NS-3

- NS-3 is a **new** simulator, written **from scratch**
  - Not really an evolution of NS-2
- Programming languages: C++, Python
  - Unlike NS-2, everything designed for C++
  - Optional Python scripting
- Project started around mid 2006
  - Still under heavy development
- Official funded partners:
  - University of Washington
    - (Tom Henderson, Craig Dowell)
  - INRIA, Sophia Antipolis
    - (Mathieu Lacage)
  - Georgia Tech University (Atlanta)
    - George Riley (main author of *GTNetS*)
    - Raj Bhattacharjea

NS-3 Modules


High-level wrappers for everything else.
No smart pointers used.
Aimed at scripting.
helper
Routing: olsr,global-routing
Internet-stack (ipv4 impl.)
Devices: csma | wifi | ...
node
mobility
common
simulator
core
Node class
NetDevice ABC
Address types (IPv4, MAC, etc.)
Queues
Socket ABC
IPv4 ABCs
Packet Sockets
Events
Scheduler
Time arithmetic
Smart pointers
Dynamic type system
Attributes
Callbacks, Tracing
Logging
Random Variables
Packets
Packet Tags
Packet Headers
Pcap/ascii file writing
Mobility Models (static, random walk, etc.)

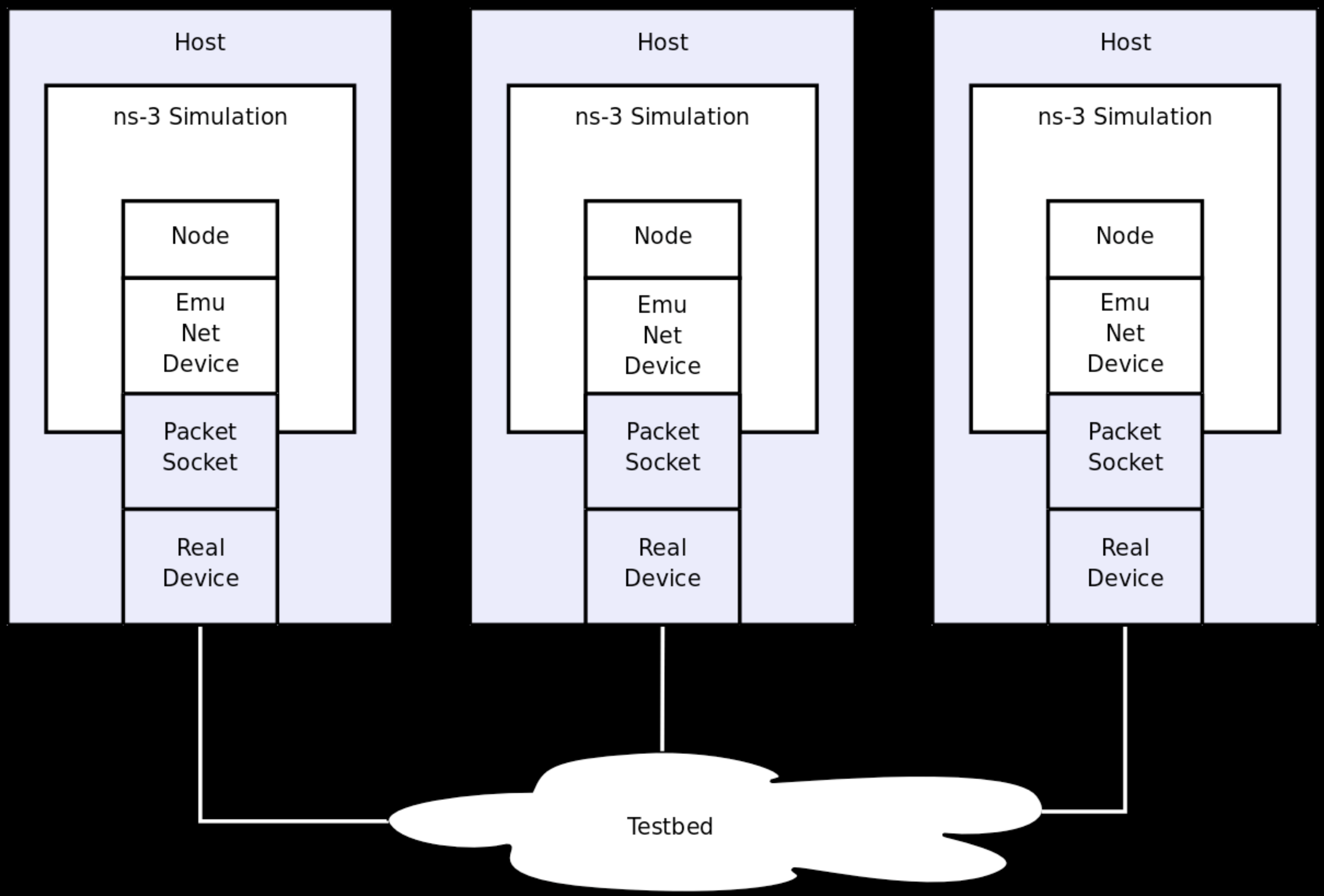
Interesting NS-3 Features

- **Scalability** features
  - Packets can have ”*virtual zero bytes*” (or *dummy bytes*)
    - For *dummy* application data that we don't care about
    - No memory is allocated for virtual zero bytes
    - <u>Reduces the memory</u> footprint of the simulation
  - Nodes have <u>optional features</u> (sort of AOP)
    - No memory waste in IPv4 stack for nodes that don't need it
    - Mobility model may not be needed
      - E.g. wired netdevices do not need to know the node position at all
    - New features can be easily added in the future
      - For example, energy models
- **Cross-layer** features
  - <u>Packet Tags</u>
    - Small units of information attached to packets
  - <u>Tracing</u>
    - Allow to report events across non-contiguous layers

Real-world Integration Features

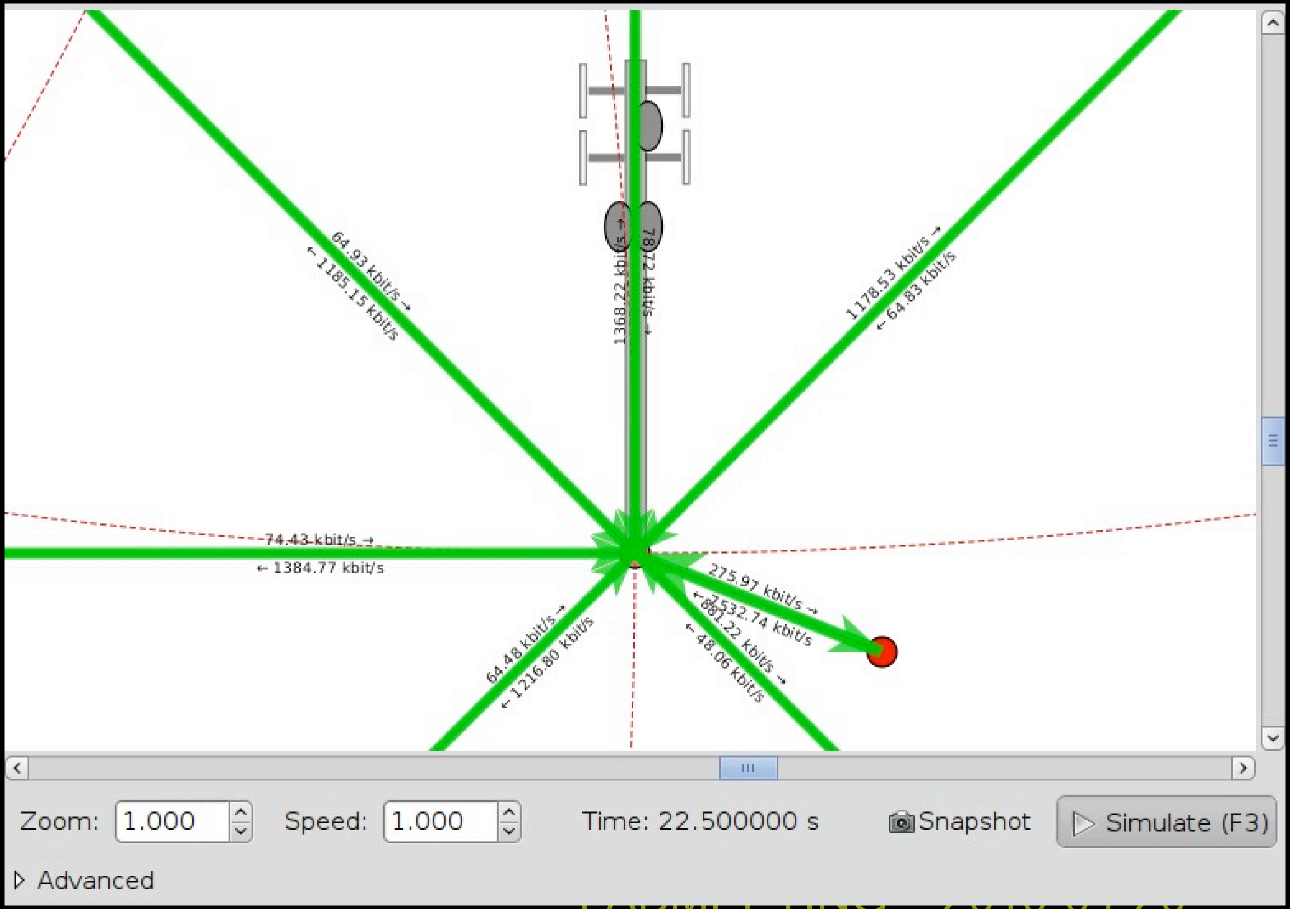
- Real world **integration** features
  - Packets can be saved to PCAP files, in a real format
    - Many tools can read PCAP files, e.g. **Wireshark**
  - Real-time scheduler
    - Simulation events synchronized to ”wall clock time”
  - ”Network Simulation Cradle”
    - Run Linux Kernel TCP/IP stack under simulation
      - Linux 2.6.18, Linux 2.6.26
  - POSIX Emulation (experimental)
    - Run unmodified POSIX programs under simulation
      - Special ELF loader converts POSIX API calls into NS-3 calls
    - Running routing daemons on NS-3 (planned)

Real world integration: EmuNetDevice



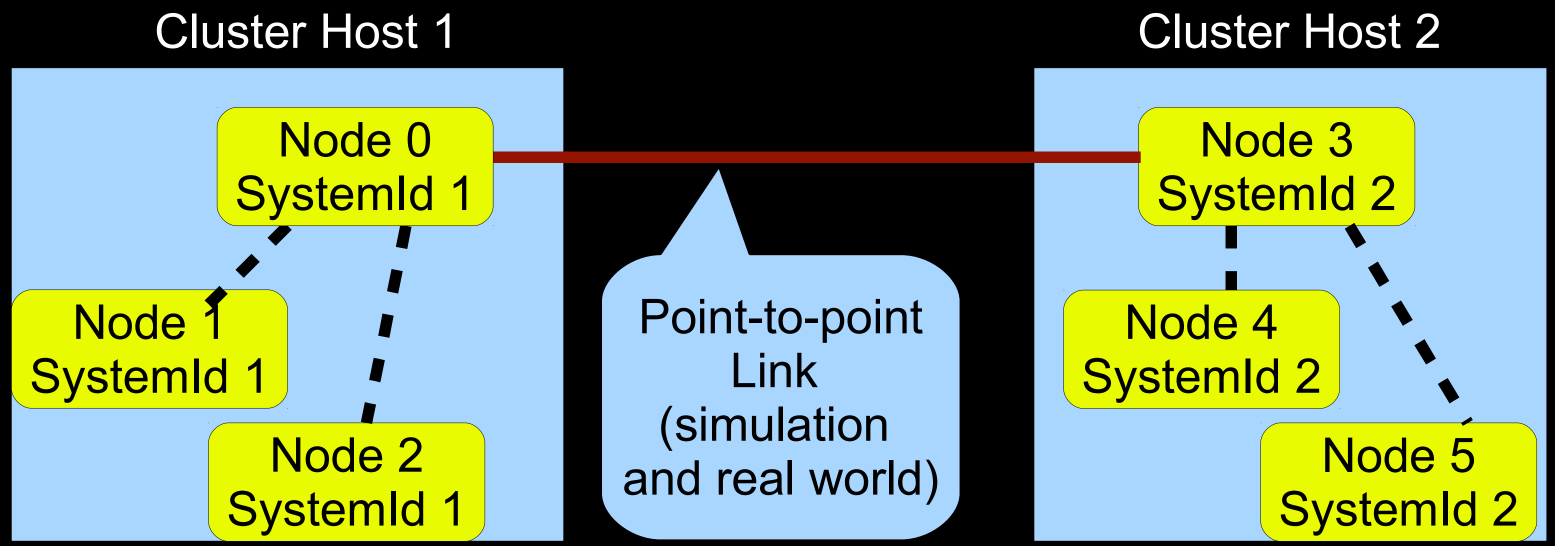
Visualization Status

- Visualization
  - Still experimental
  - Several ongoing attempts, none yet integrated
    - Example: ns-3-pyviz
      - (demoed in SIGCOMM workshop, Aug. 2008)



Distributed Simulation using MPI

- MPI: Message Passing Interface
  - Library (and protocol) for distributed applications
- New in NS-3.8, an MPI Simulator
  - Nodes in the simulation assigned different ***System Ids***
  - Nodes with different System Ids run on different cluster machines
  - Nodes on different machines may communicate using point-to-point links only



Link layer models

- Point-to-point (PPP links)
- Csma (Ethernet links)
- Bridge: 802.1D Learning Bridge
- Wifi (802.11 links)
  - EDCA QoS support (but not HCCA)
  - Both infrastructure (with beacons), and adhoc modes
- Mesh
  - 802.11s (but no legacy 802.11 stations supported yet)
  - ”Flame”: Forwarding LAyer for MEshing protocol
    - ”Easy Wireless: broadband ad-hoc networking for emergency services”
- Wimax: 802.16 (new in NS 3.8)
  - ”supports the four scheduling services defined by the 802.16-2004 standard”
- Tap-bridge, emu: testbed integration

Routing

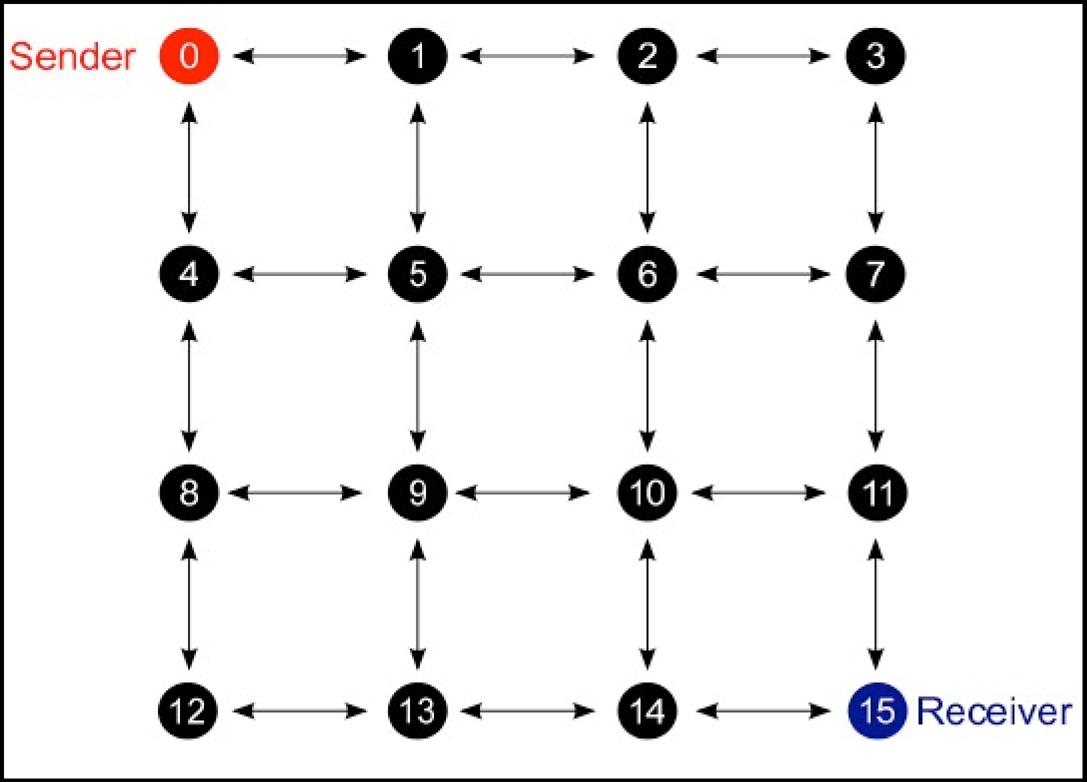
- Adhoc:
  - OLSR (RFC 3626)
    - Since NS 3.8 with full HNA support (thanks Latih Suresh)
  - AODV (RFC 3561)
- ”Global routing” (aka GOD routing)
  - Just computes static routes on simulation start
- Nix-vector Routing
  - Limited but high performance static routing
  - For simulations with thousands of wired nodes
- List-routing
  - Joins multiple routing protocols in the same node
  - For example: static routing tables + OLSR + AODV

Applications (traffic generators)

- **Onoff**
  - Generates streams, alternating on-and-off periods
  - Highly parameterized
    - Can be configured to generate many types of traffic
      - E.g. OnTime=1 and OffTime=0 means CBR
    - Works with either UDP or TCP
- **Packet sink**: receives packets or TCP connnections
- **Ping6, v4ping**: send ICMP ECHO request
- **Udp-client/server**: sends UDP packet w/ sequence number
- **Udp-echo**: sends UDP packet, no sequence number
- **Radvd**: router advertisement (for IPv6)

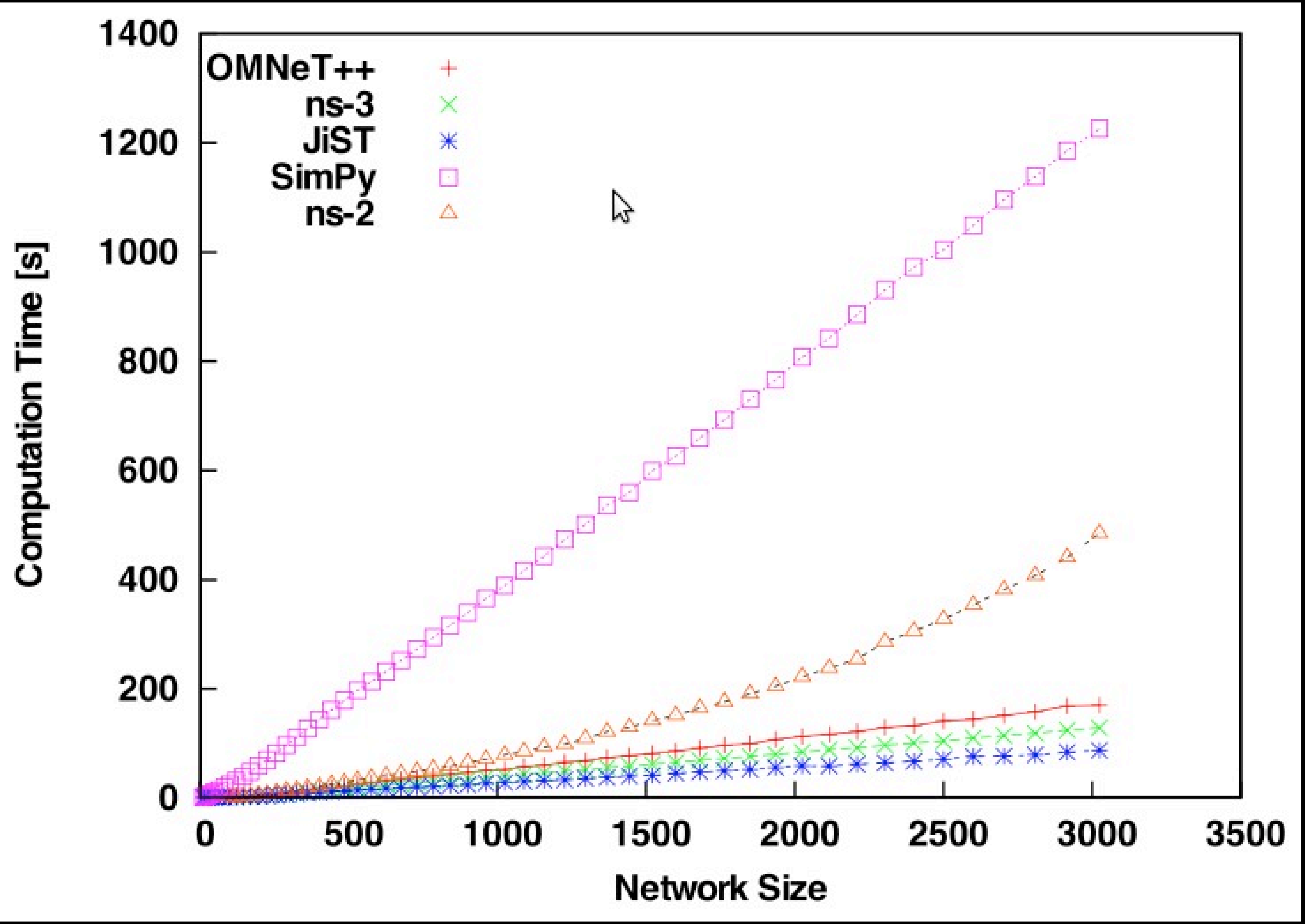
NS 3: Performance

- Source: E. Weingärtner, H. Lehn, and K. Wehrle, *"A performance comparison of recent network simulators"*, IEEE International Conference on Communications 2009.



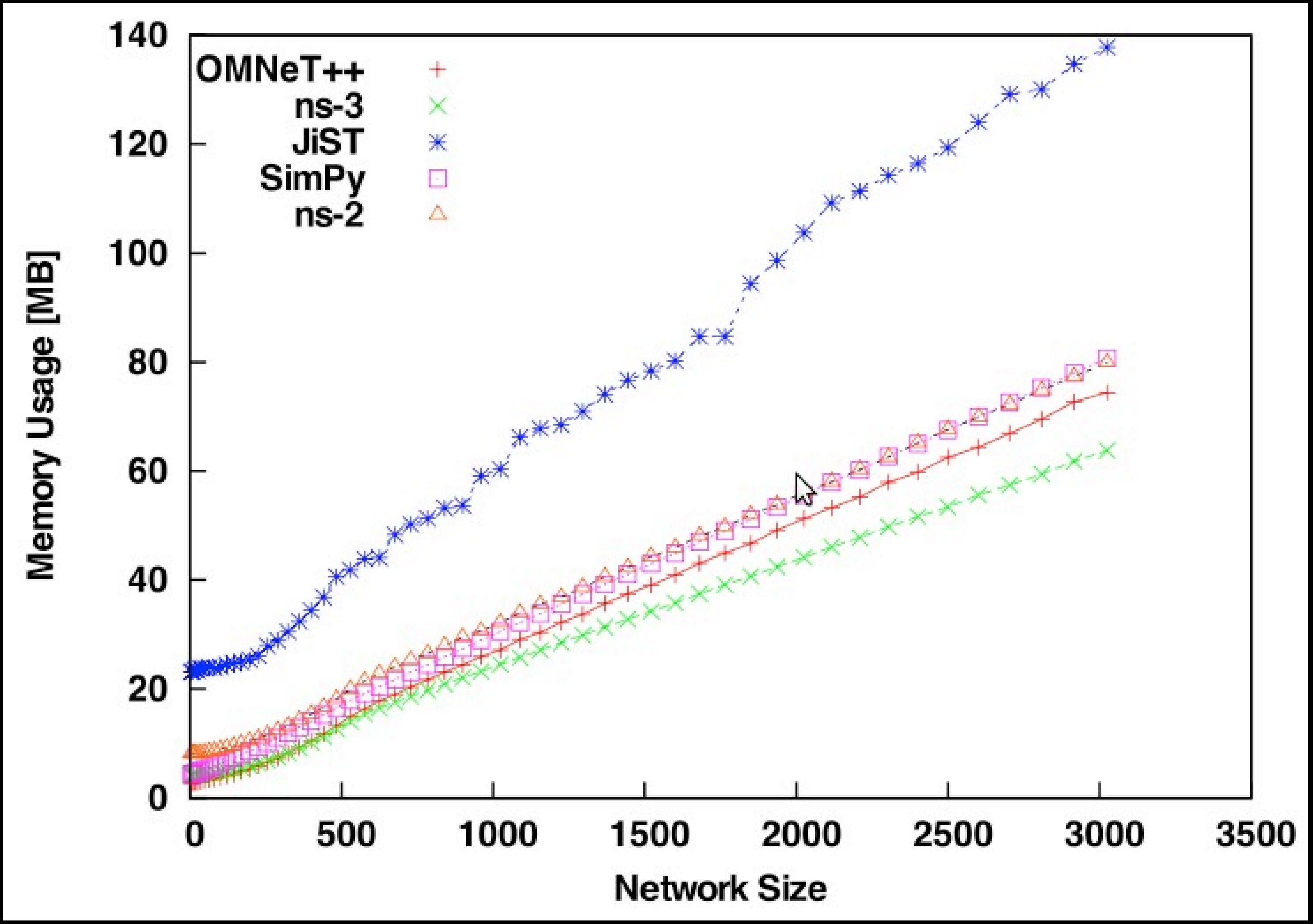
- *"One sending node generates one packet every second and broadcasts it to its neighbors"*
- *"The neighboring nodes relay unseen messages after a delay of one second, thus flooding the entire network."*

NS-3 Performance: Time



- Source: E. Weingärtner, H. Lehn, and K. Wehrle, *"A performance comparison of recent network simulators"*, IEEE International Conference on Communications 2009.

NS-3 Performance: Memory



- Source: E. Weingärtner, H. Lehn, and K. Wehrle, *"A performance comparison of recent network simulators"*, IEEE International Conference on Communications 2009.

(Preliminary) Conclusions

- NS-3 contains inovative and useful features
  - Scalable
  - Flexible
  - Clean design
  - Real-world (e.g. testbed) integration
- NS-3 has good performance
  - One of the fastest simulators around
  - The most memory efficient simulator around
- However
  - Not many models available for NS-3 yet
  - No GUI to build topology
  - Visualization still experimental

NS-3 internal APIs overview

Simulator Core

- Time is not manipulated directly: the Time class
  - Time class supports high precision 128 bit time values (nanosecond precision)

```
Time t1 = Seconds (10);
Time t2 = t1 + MilliSeconds (100);
std::cout << t2.GetSeconds () << std::endl; // t2 = 10.1
```

- Get current time:
  - `Time now = Simulator::Now ();`
- Schedule an event to happen in 3 seconds:
  - ```
    void MyCallback (T1 param1, T2 param2) {...}
    [...]
    Simulator::Schedule (Seconds (3), MyCallback, param1, param2);
    ```
    - Values *param1* and *param2* passed as callback parameters
  - Also works with instance methods:

    ```
    Simulator::Schedule (Seconds (3), &MyClass::Method,
                         instancePtr, param1, param2);
    ```
    ```

Random Variables

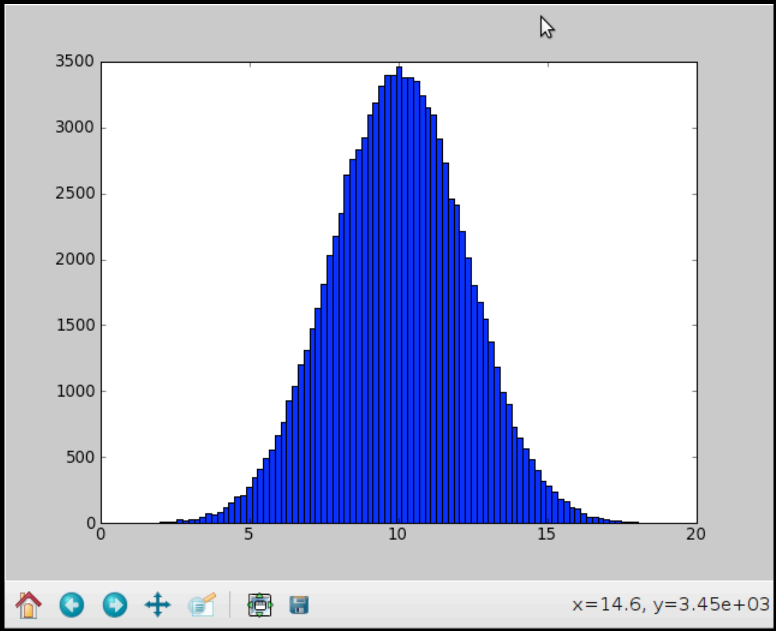
- Currently implemented distributions
  - Uniform: values uniformly distributed in an interval
  - Constant: value is always the same (not really random)
  - Sequential: return a sequential list of predefined values
  - Exponential: exponential distribution (poisson process)
  - Normal (gaussian)
  -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

(μ) (σ)

```
import pylab
import ns3

rng = ns3.NormalVariable(10.0, 5.0)
x = [rng.GetValue() for t in range(100000)]

pylab.hist(x, 100)
pylab.show()
```



Memory Management

- Many NS-3 objects use automatic garbage collection
- <u>Reference counting</u>
  - ```
    Packet *p = new Packet; # refcount initialized to 1
    p->Ref (); # refcount becomes 2
    p->Unref (); # refcount becomes 1
    p->Unref (); # refcount becomes 0, packet is freed
    ```
- <u>Smart pointers</u>
  - Manual reference counting is error prone
    - Can easily lead to memory errors
  - Smart pointers
    - Take care of all the reference counting work
    - Otherwise they behave like normal pointers
  - Example:

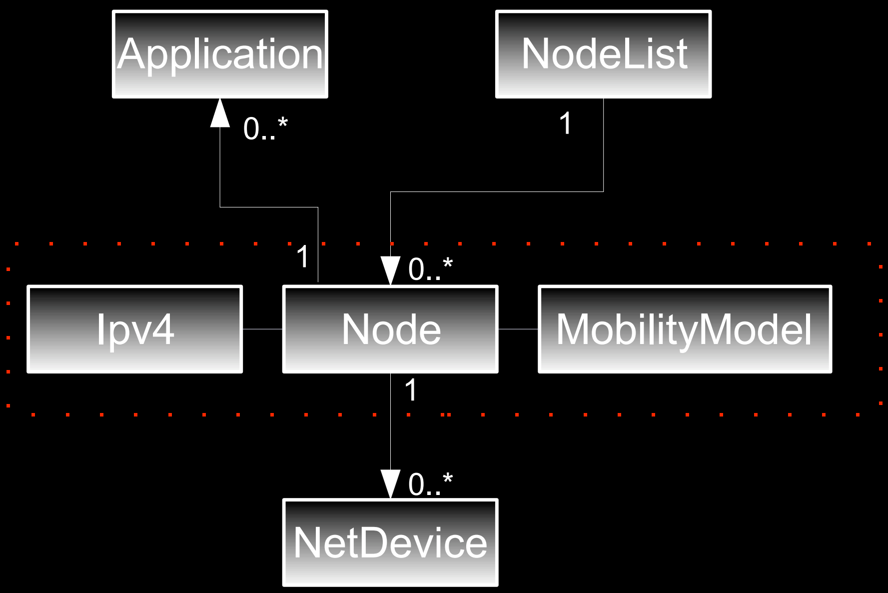
```
void MyFunction ()
{
  Ptr<Packet> p = Create<Packet> (10);
  std::cerr << "Packet size: " << p->GetSize () << std::endl;
} # Packet is released (smart pointer goes out of scope)
```
```

Packets

- Packet objects used *vertically* in NS-3 to represent:
  - Units of information sent and received by applications
  - Information chunks of what will become a real packet (similar sk_buff in Linux kernel)
  - Simulated packets and L2/L1 frames being transmitted
- Basic Usage
  - Create empty packet
    - `Ptr<Packet> packet = Create<Packet> ();`
  - Create packet with 10 ”dummy” bytes
    - `Ptr<Packet> packet = Create<Packet> (10);`
    - ”Dummy” bytes are simulated as being there, but do not actually occupy any memory (reduces memory footprint)
  - Create packet with user data
    - `Ptr<Packet> packet = Create<Packet> (”hello”, 5);`
  - Copy a packet
    - `Ptr<Packet> packet2 = packet1->Copy ();`
    - Note: packet copy is usually cheap (copy-on-write)

Nodes

- Node class
  - Represents a network element
  - <u>May</u> have an ***IPv4 stack*** object
    - But it is completely optional!
  - <u>May</u> have a ***mobility model***
    - But it is optional, e.g. CsmaNetDevice needs no mobility model
  - Contains a list of ***NetDevice***s
  - Contains a list of ***Applications***



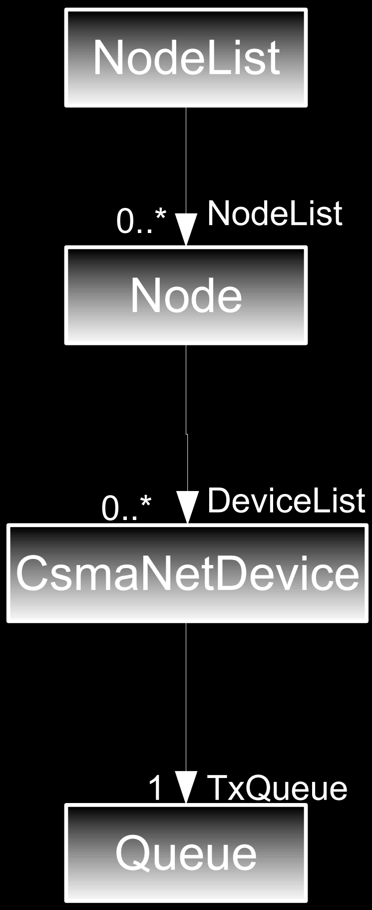
- NodeList class (singleton)
  - Tracks all nodes ever created
  - Node index <=> Ptr conversions

Tracing (by example)

```
uint64_t g_packetDrops = 0;
uint64_t g_packetDropBytes = 0;

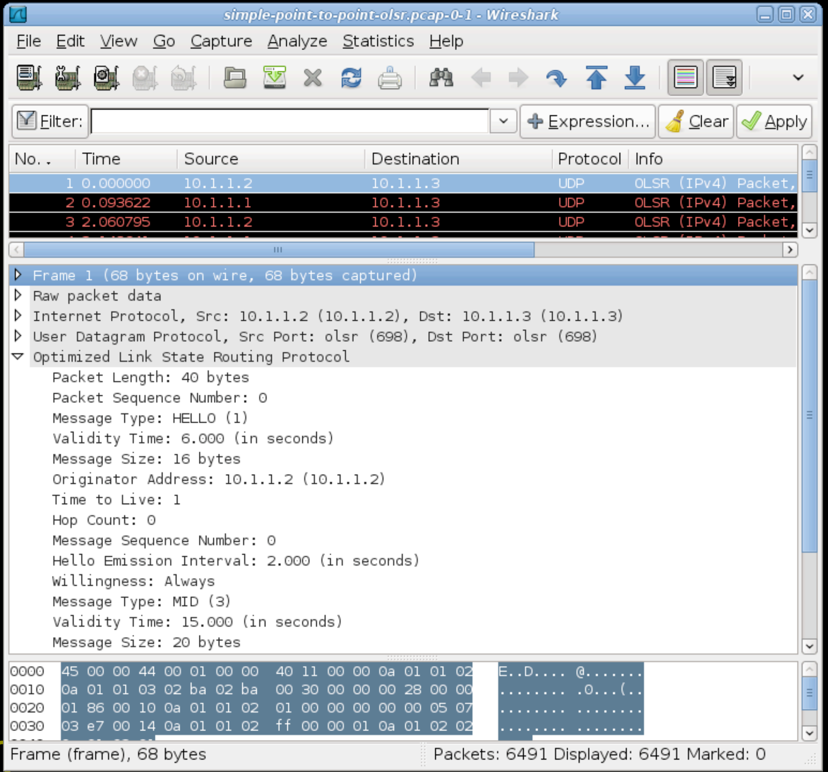

void TraceDevQueueDrop (std::string context,
                        Ptr<const Packet> droppedPacket)
{
  g_packetDrops += 1;
  g_packetDropBytes += droppedPacket->GetSize ();
}


int main (int argc, char *argv[])
{
  […]
  Config::Connect ("/NodeList/*/DeviceList/*/TxQueue/Drop",
                   MakeCallback (&TraceDevQueueDrop));
  […]
}
```



Packet: Headers and Trailers

- Packets support *headers* and *trailers*
  - Headers an trailers are implemented as classes that
    - Implement a **Serialize** method:
      - Writes the header information as a byte stream;
    - Implement a **Deserialize** method:
      - Reads the header information from a byte stream;
  - Headers and trailers used to implement protocols
  - Packets contain exact byte contents
    - They are not just structures as in NS-2
    - Allows writing pcap trace files, readable from wireshark



- LLC/SNAP example (from ns-3):

```
uint32_t LlcSnapHeader::GetSerializedSize (void) const
{
  return 1 + 1 + 1 + 3 + 2;
}
void LlcSnapHeader::Serialize (Buffer::Iterator start) const
{
  Buffer::Iterator i = start;
  uint8_t buf[] = {0xaa, 0xaa, 0x03, 0, 0, 0};
  i.Write (buf, 6);
  i.WriteHtonU16 (m_etherType);
}
uint32_t LlcSnapHeader::Deserialize (Buffer::Iterator start)
{
  Buffer::Iterator i = start;
  i.Next (5+1);   // skip 6 bytes, don't care about content
  m_etherType = i.ReadNtohU16 ();
  return GetSerializedSize ();
}
```

- Adding a header:
  - ```
    LlcSnapHeader llcsnap;
    llcsnap.SetType (0x0800); # Ipv4
    packet->AddHeader (llcsnap);
    ```
- Removing a header:
  - ```
    LlcSnapHeader llcsnap;
    if (packet->RemoveHeader (llcsnap) {
        std::cout << llcsnap.GetType () << std::endl;
    }
    ```

Callback Objects

- NS-3 Callback class implements ***function objects***
  - Type safe callbacks, manipulated by value
    - Used for example in sockets and tracing
- Example

```
double MyFunc (int x, float y) {
   return double (x + y) / 2;
}
[...]
Callback<double, int, float> cb1;
cb1 = MakeCallback (MyFunc);
double result = cb1 (2, 3); // result receives 2.5
[...]
class MyClass {
public: double MyMethod (int x, float y) {
   return double (x + y) / 2;
};
[...]
Callback<double, int, float> cb1;
MyClass myobj;
cb1 = MakeCallback (&MyClass::MyMethod, &myobj);
double result = cb1 (2, 3); // result receives 2.5
```

NS-3 Sockets

- 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_
   addr);
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.si
   n_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 ())*

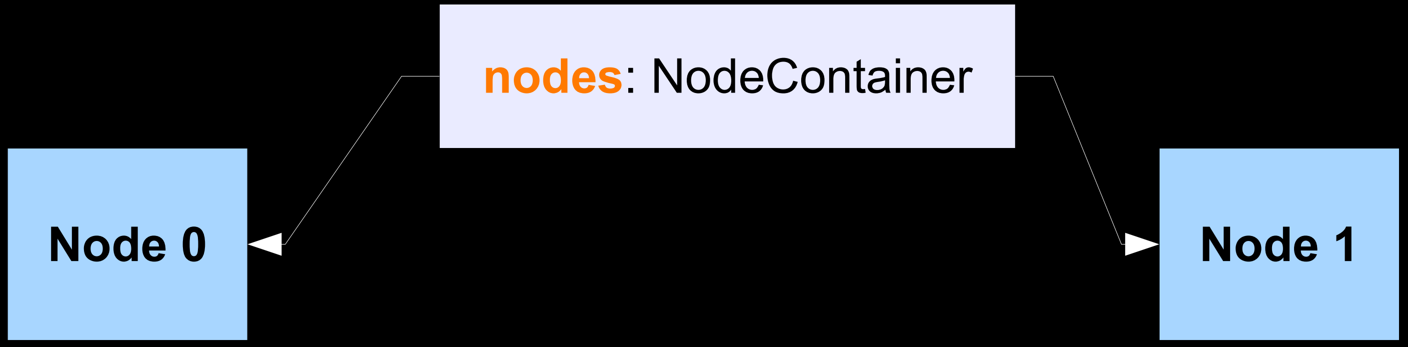
```
void MySocketReceive (Ptr<Socket> sk,
                      Ptr<Packet> packet)
{
...
}
```

Tutorial

examples/tutorial/first.cc (1 / 6)

```
int main (int argc, char *argv[])
{
  LogComponentEnable ("UdpEchoClientApplication",
                      LOG_LEVEL_INFO);
  LogComponentEnable ("UdpEchoServerApplication",
                      LOG_LEVEL_INFO);


  NodeContainer nodes;
  nodes.Create (2);
```



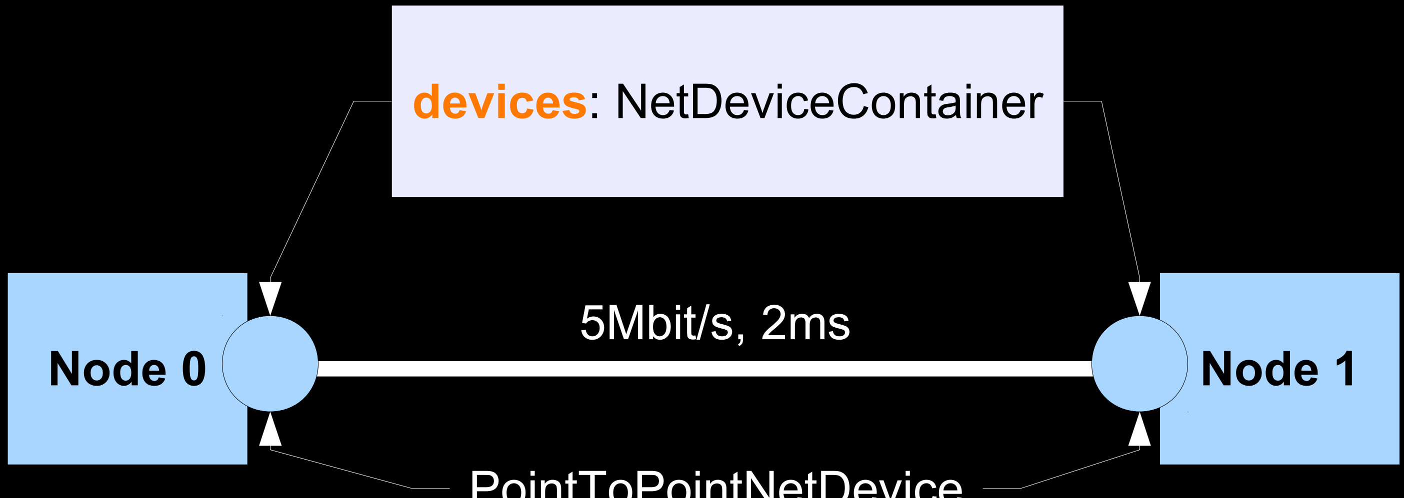
examples/tutorial/first.cc (2 / 6)

```
PointToPointHelper pointToPoint;

pointToPoint.SetDeviceAttribute ("DataRate",
                                 StringValue ("5Mbps"));

pointToPoint.SetChannelAttribute ("Delay",
                                  StringValue ("2ms"));

NetDeviceContainer devices;
devices = pointToPoint.Install (nodes);
```

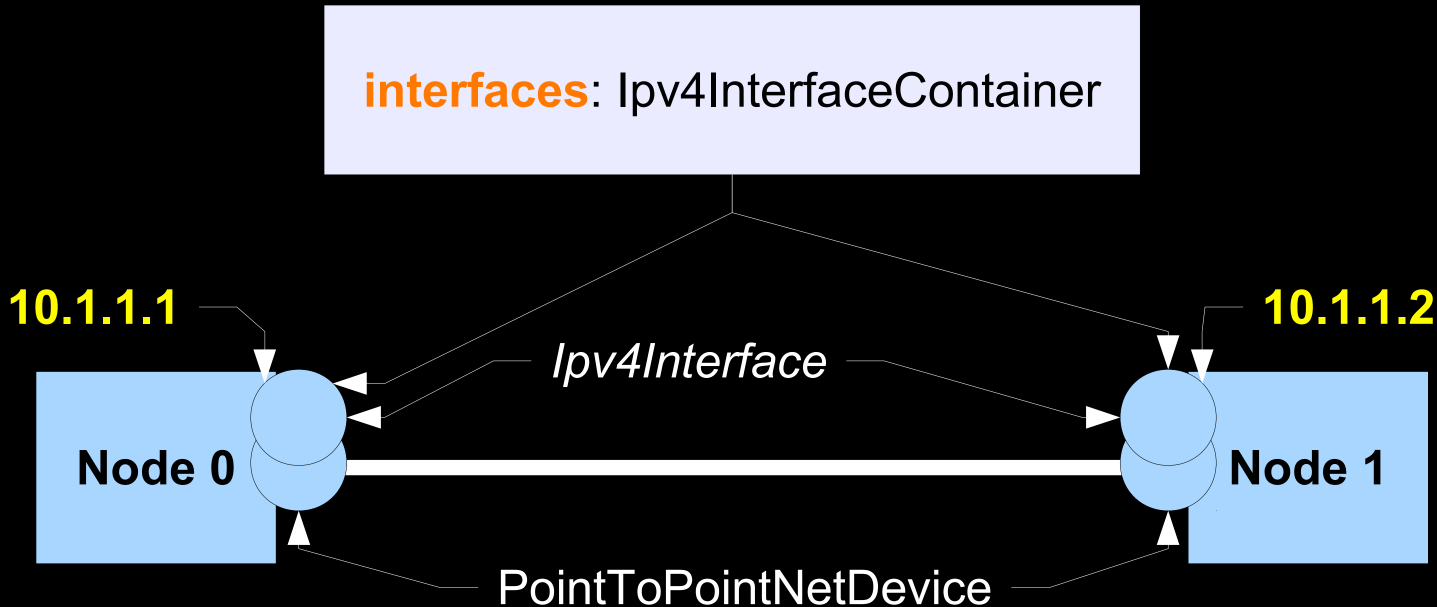


examples/tutorial/first.cc (3 / 6)

```
InternetStackHelper stack;
stack.Install (nodes);

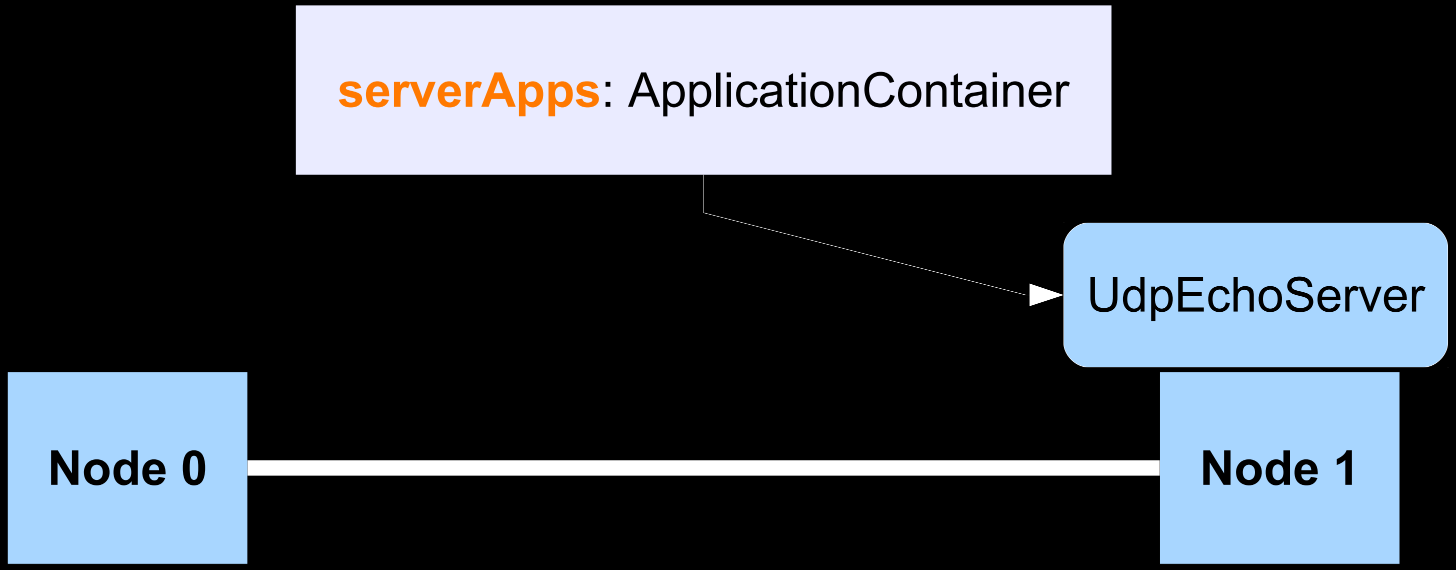
Ipv4AddressHelper address;
address.SetBase ("10.1.1.0", "255.255.255.0");

Ipv4InterfaceContainer interfaces =
                         address.Assign (devices);
```



examples/tutorial/first.cc (4 / 6)

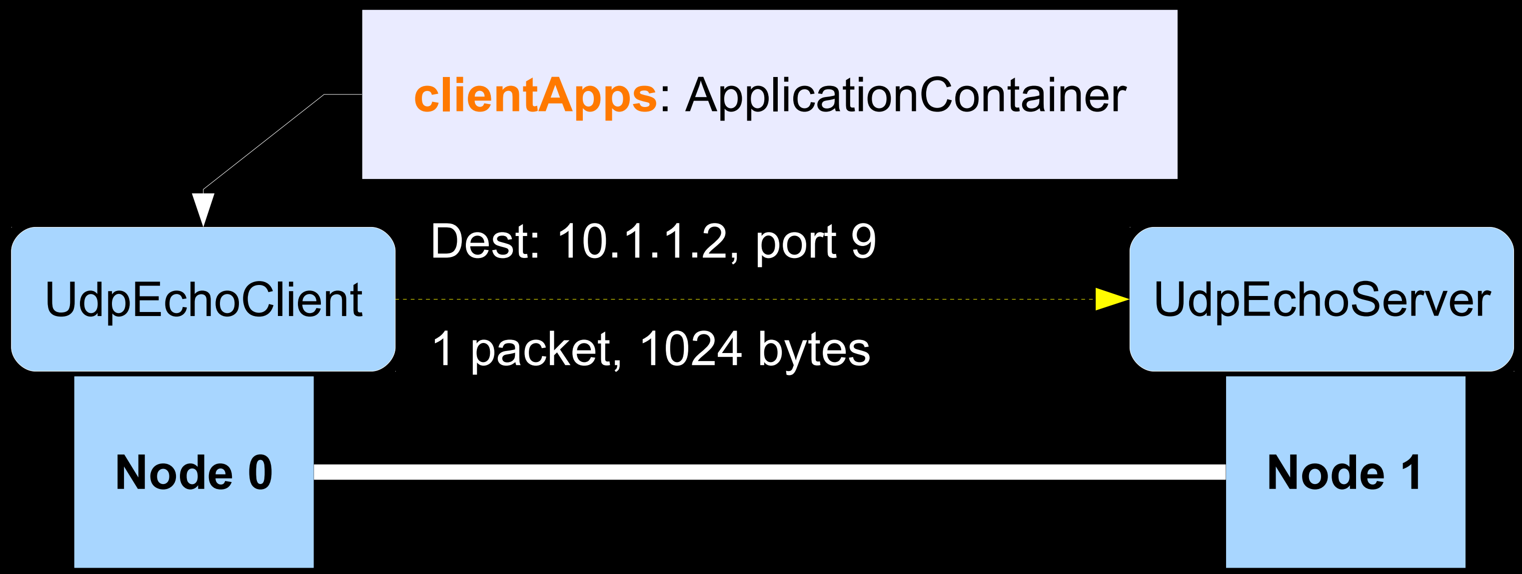
```
UdpEchoServerHelper echoServer (9);
ApplicationContainer serverApps =
                echoServer.Install (nodes.Get (1));
serverApps.Start (Seconds (1.0));
serverApps.Stop (Seconds (10.0));
```



examples/tutorial/first.cc (5 / 6)

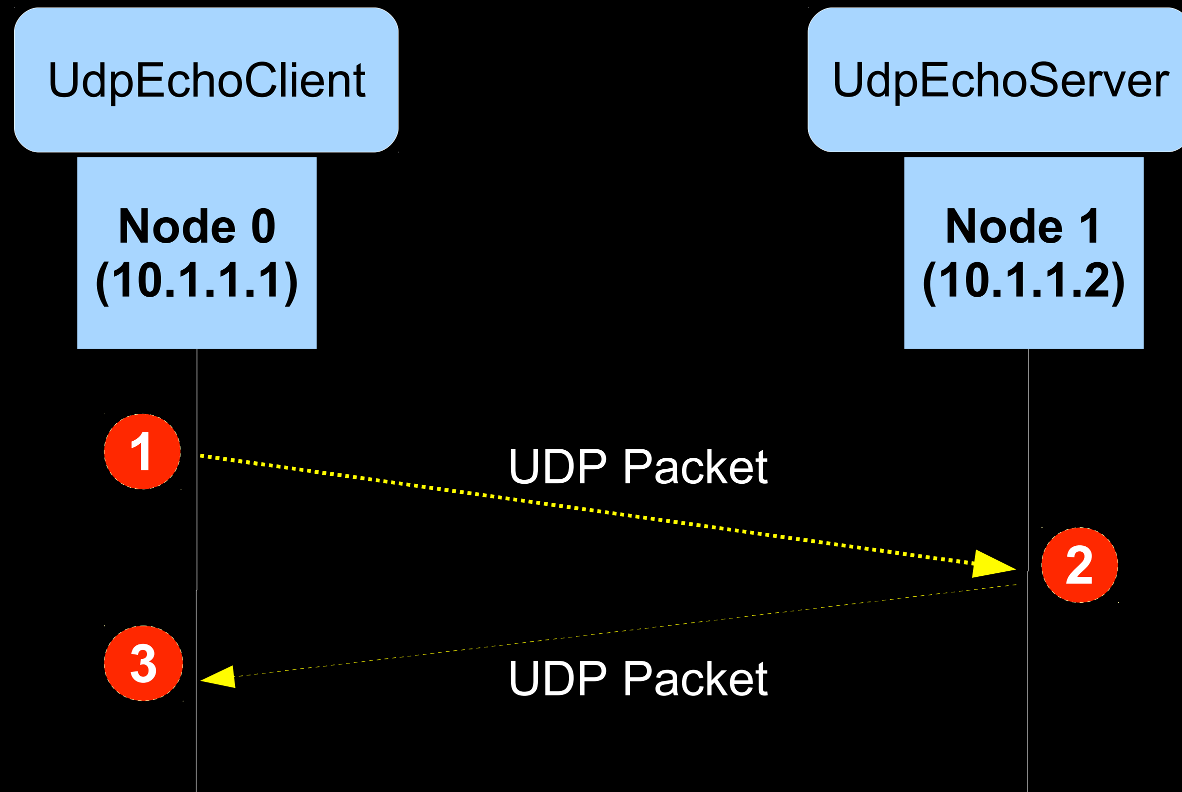
```
UdpEchoClientHelper echoClient (interfaces.GetAddress (1), 9);
echoClient.SetAttribute ("MaxPackets", UintegerValue (1));
echoClient.SetAttribute ("Interval", TimeValue (Seconds (1.)));
echoClient.SetAttribute ("PacketSize", UintegerValue (1024));

ApplicationContainer clientApps =
                           echoClient.Install (nodes.Get (0));
clientApps.Start (Seconds (2.0));
clientApps.Stop (Seconds (10.0));
```



examples/tutorial/first.cc (6 / 6)

```
[…]
  Simulator::Run ();
  Simulator::Destroy ();
  return 0;
}
```




```
$ ./waf --run first
[…]
Sent 1024 bytes to 10.1.1.2
Received 1024 bytes from 10.1.1.1
Received 1024 bytes from 10.1.1.2
```

1 2 3

Same thing but in **Python!**

```
import ns3

ns3.LogComponentEnable("UdpEchoClientApplication", ns3.LOG_LEVEL_INFO)
ns3.LogComponentEnable("UdpEchoServerApplication", ns3.LOG_LEVEL_INFO)

nodes = ns3.NodeContainer()
nodes.Create(2)

pointToPoint = ns3.PointToPointHelper()
pointToPoint.SetDeviceAttribute("DataRate", ns3.StringValue("5Mbps"))
pointToPoint.SetChannelAttribute("Delay", ns3.StringValue("2ms"))

devices = pointToPoint.Install(nodes)

stack = ns3.InternetStackHelper()
stack.Install(nodes)

address = ns3.Ipv4AddressHelper()
address.SetBase(ns3.Ipv4Address("10.1.1.0"), ns3.Ipv4Mask("255.255.255.0"))
interfaces = address.Assign(devices)

echoServer = ns3.UdpEchoServerHelper(9)

serverApps = echoServer.Install(nodes.Get(1))
serverApps.Start(ns3.Seconds(1.0))
serverApps.Stop(ns3.Seconds(10.0))

echoClient = ns3.UdpEchoClientHelper(interfaces.GetAddress(1), 9)
echoClient.SetAttribute("MaxPackets", ns3.UintegerValue(1))
echoClient.SetAttribute("Interval", ns3.TimeValue(ns3.Seconds (1.0)))
echoClient.SetAttribute("PacketSize", ns3.UintegerValue(1024))

clientApps = echoClient.Install(nodes.Get(0))
clientApps.Start(ns3.Seconds(2.0))
clientApps.Stop(ns3.Seconds(10.0))

ns3.Simulator.Run()
ns3.Simulator.Destroy()
```

wifi-olsr-flowmon.py (1/8)

```
import sys
import ns3

DISTANCE = 150 # (m)
NUM_NODES_SIDE = 3

def main(argv):

    cmd = ns3.CommandLine()

    cmd.NumNodesSide = None
    cmd.AddValue("NumNodesSide", "Grid side number of nodes (total
number of nodes will be this number squared)")

    cmd.Results = None
    cmd.AddValue("Results", "Write XML results to file")

    cmd.Plot = None
    cmd.AddValue("Plot", "Plot the results using the matplotlib python
module")

    cmd.Parse(argv)
```

wifi-olsr-flowmon.py (2/8)

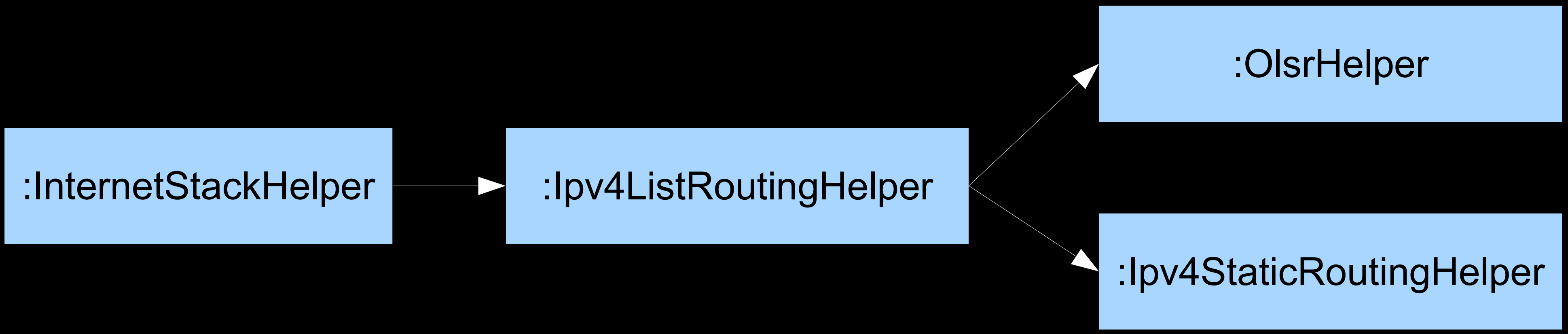
```
(...continued from main...)

wifi = ns3.WifiHelper.Default()
wifiMac = ns3.NqosWifiMacHelper.Default()
wifiPhy = ns3.YansWifiPhyHelper.Default()
wifiChannel = ns3.YansWifiChannelHelper.Default()
wifiPhy.SetChannel(wifiChannel.Create())
wifi.SetRemoteStationManager("ns3::ArfWifiManager")
wifiMac.SetType ("ns3::AdhocWifiMac",
     "Ssid", ns3.SsidValue(ns3.Ssid("wifi-default")))
```

wifi-olsr-flowmon.py (3/8)

```
internet = ns3.InternetStackHelper()
list_routing = ns3.Ipv4ListRoutingHelper()
olsr_routing = ns3.OlsrHelper()
static_routing = ns3.Ipv4StaticRoutingHelper()
list_routing.Add(static_routing, 0)
list_routing.Add(olsr_routing, 100)  # OLSR takes precedence!
internet.SetRoutingHelper(list_routing)

ipv4Addresses = ns3.Ipv4AddressHelper()
ipv4Addresses.SetBase(ns3.Ipv4Address("10.0.0.0"),
                      ns3.Ipv4Mask("255.255.255.0"))
```



wifi-olsr-flowmon.py (4/8)

```
    port = 9   # Discard port(RFC 863)
    onOffHelper = ns3.OnOffHelper("ns3::UdpSocketFactory",
ns3.Address(ns3.InetSocketAddress(ns3.Ipv4Address("10.0.0.1"), port)))

    onOffHelper.SetAttribute("DataRate",
ns3.DataRateValue(ns3.DataRate("100kbps")))

    onOffHelper.SetAttribute("OnTime",
ns3.RandomVariableValue(ns3.ConstantVariable(1)))

    onOffHelper.SetAttribute("OffTime",
ns3.RandomVariableValue(ns3.ConstantVariable(0)))
```

wifi-olsr-flowmon.py (5/8)

```
addresses = []
nodes = []

# C++: for (int xi = 0; xi < num_nodes_side; xi++) {
for xi in range(num_nodes_side):
    # C++: for (int yi = 0; yi < num_nodes_side; yi++) {
    for yi in range(num_nodes_side):

        node = ns3.Node()
        nodes.append(node)

        mobility = ns3.ConstantPositionMobilityModel()
        mobility.SetPosition(ns3.Vector(xi*DISTANCE,
                                        yi*DISTANCE, 0))
        node.AggregateObject(mobility)

        devices = wifi.Install(wifiPhy, wifiMac, node)

        internet.Install(node) # adds Ipv4 and static+OLSR routing
        ipv4_interfaces = ipv4Addresses.Assign(devices)
        addresses.append(ipv4_interfaces.GetAddress(0))
```

wifi-olsr-flowmon.py (6/8)

```
for i, node in enumerate(nodes):
    destaddr = addresses[(len(addresses) - 1 - i) % len(addresses)]
    onOffHelper.SetAttribute("Remote",
         ns3.AddressValue(ns3.InetSocketAddress(destaddr, port)))
    app = onOffHelper.Install(ns3.NodeContainer(node))
    app.Start(ns3.Seconds(ns3.UniformVariable(20, 30).GetValue()))


flowmon_helper = ns3.FlowMonitorHelper()
monitor = flowmon_helper.InstallAll()
monitor.SetAttribute("DelayBinWidth", ns3.DoubleValue(0.001))
monitor.SetAttribute("JitterBinWidth", ns3.DoubleValue(0.001))
monitor.SetAttribute("PacketSizeBinWidth", ns3.DoubleValue(20))

ns3.Simulator.Stop(ns3.Seconds(44.0))
```

wifi-olsr-flowmon.py (7/8)

```
ns3.Simulator.Run()

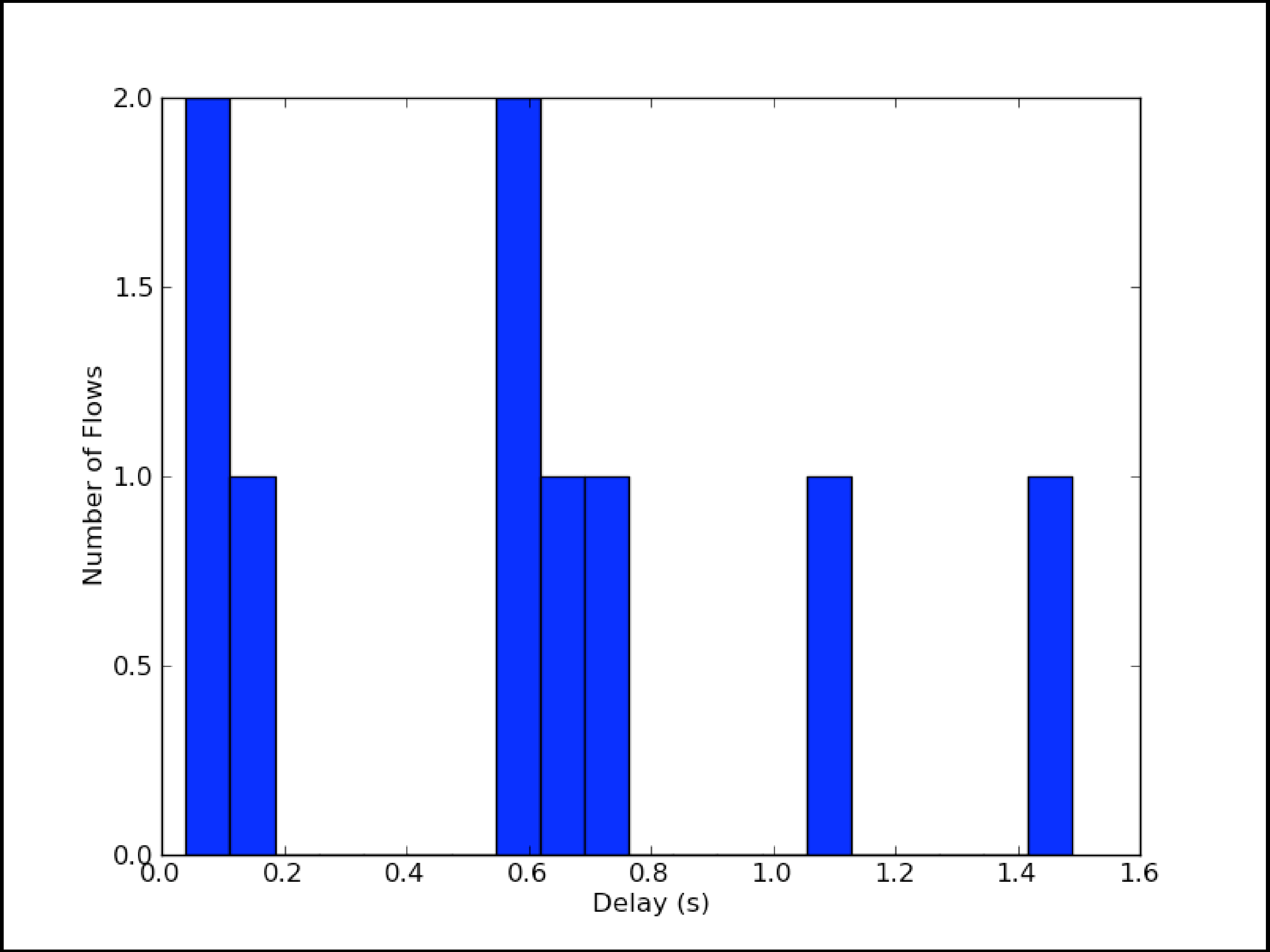
classifier = flowmon_helper.GetClassifier()

if cmd.Plot is not None: # if --Plot cmdline option given:
    import pylab
    delays = []
    for flow_id, flow_stats in monitor.GetFlowStats():
        # filter out UDP port 698 (OLSR)
        tupl = classifier.FindFlow(flow_id)
        if tupl.protocol == 17 and tupl.sourcePort == 698:
            continue

        delays.append(flow_stats.delaySum.GetSeconds()
                      / flow_stats.rxPackets)

    pylab.hist(delays, 20)
    pylab.xlabel("Delay (s)")
    pylab.ylabel("Number of Flows")
    pylab.show()
```

wifi-olsr-flowmon.py (8/8)



Questions?

Mobility Models

- 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

Getting Started: Linux

- Building it
  1) sudo apt-get install build-essential g++ python mercurial # (Ubuntu)
  2) hg clone http://code.nsnam.org/ns-3-allinone/
  3) cd ns-3-allinone
  4) ./download.py *# will download components*
  5) ./build.py *# will build NS-3*
  6) cd ns-3-dev
- Running example programs
  - Programs are built as build/*<variant>/path/program_name*
    - *<variant>* is either *debug* or *optimized*
  - Using waf --shell
    1) ./waf –shell
    2) ./build/debug/examples/simple-point-to-point
  - Using waf –run
    1) ./waf –run simple-point-to-point

Getting Started: Windows

- Building it

```
1) Install build tools
  1) Cygwin or Mingw GCC (g++)
  2) Python: http://www.python.org
  3) Mercurial: http://mercurial.berkwood.com/
2) hg clone http://code.nsnam.org/ns-3.0.11/
3) cd ns-3.0.11
4) waf configure # optional: -d optimized
5) waf check  # runs unit tests
```

- Rest of instructions the same as in Linux...

Packet: Tags

- Tags
  - Small chunks of information
  - Any number of tags can be attached a packet
  - Tags are keyed by the a structure type itself
    - Ptr<Packet> p;
    - MyTag tag;
    - p->AddTag (tag)
    - p->PeekTag (tag)
  - New tag types are defined similarly to header types
- Tags can be used to:
  - Attach context information to a packet
    - Example: NetDevice attaches destination MAC address when queueing, retrieves it when dequeuing for transmission
  - Convey additional information across layers

class Object

- **Object** is the base class for many important classes:
  - Node, NetDevice, Application, Socket, ...
- class Object provides many useful features
  - Basic memory management (reference counting)
  - Advanced memory management (the Dispose method)
    - Dispose/DoDispose: used to break reference counting loops
      - Node => list(Application); Application => Node
  - Object aggregation
    - COM-like interface query mechanism
    - Instead of a huge class, split class into several objects:
      - Node, Ipv4, [Udp/Tcp]SocketFactory, Mobility,...
    - Example: from a Node object, see if it supports Ipv4

```
void MyFunction (Ptr<Node> node)
{
  Ptr<Ipv4> ipv4 = node->GetObject<Ipv4> ();
  if (ipv4 != NULL)
      std::cerr << "Node has " << ipv4->GetNRoutes ()
                     << "routes." << std::endl;
}
```

  - Tracing hooks

Object and TypeId

- TypeId: working around C++ limitations
  - In C++, classes are not *first-class objects*
- TypeId is an object that describes a class type:
  - Type name
  - List of *attributes* or *trace sources*
- TypeId implements the *Factory* Design Pattern
  - Example: to create an object from type name:
- ```
  TypeId objType = TypeId::LookupByName ("StaticMobilityModel")
  Ptr<Object> mobilityModel = objType.CreateObject ()
  ```
  ```

Object and TypeId (cont.)

- Because of the TypeId system, creating Object instances should be done with:
  - `Ptr<ClassName> obj = CreateObject<ClassName> (...parameters)`
- Defining new Object subclasses needs special care:
  - Must define a GetTypeId static method, like this:

```
class MyClass : public MyParent
{
public:
  MyClass (ParamType1 p1, ...);
  static TypeId  GetTypeId (void);
[...]
};

TypeId
MyClass::GetTypeId (void)
{
  static TypeId tid = TypeId ("MyClass")
    .SetParent<MyParent> ()
    .AddConstructor<MyClass, ParamType1, ... > ();
  return tid;
}
```

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`

Applications and Sockets

- Each Node contains a list of Applications
  - Applications are like *processes* in a normal system
- Applications contain a number of Sockets
  - Sockets represent communication end points
  - NS-3 sockets modelled after the BSD socket API
- Example uses of Applications
  - Traffic generators (e.g. OnOffApplication)
  - Traffic sinks (e.g. to respond to connection requests)
  - Routing agents, higher level protocols
    - Whatever normally runs in userspace in a UNIX system
- Sockets creation: a *socket factory* Node interface:

```
Ptr<SocketFactory> udpFactory =
   node->GetObject<SocketFactory>
                  (TypeId::LookupByName ("Udp"));
Ptr<Socket> socket = udpFactory->CreateSocket ();
```