Experimentation with ns-3

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Goals of this tutorial

- Understand the goals of the ns-3 project
- Learn what has been done to achieve these goals
- Identify future work directions

Tutorial schedule

1. 14h00-15h00: Introduction
2. 15h00-16h00: The ns-3 architecture
3. 16h00-17h00: The ns-3 object model

Part I

Introduction

Outline

Simulation considered harmful

Why not reuse an existing simulator ?

What is so special about ns-3 ?

What we learned along the way

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Simulation considered harmful

Why not reuse an existing simulator ?

What is so special about ns-3 ?

What we learned along the way

Recent history (1995-2005)

- ns-2 became the main choice for research usage. Search of ACM Digital Library papers citing simulation, 2001-04:

	ns-2	OPNET	QualNet/Glomosim
$\geq$ layer 4	123 (75%)	30 (18%)	11 (7%)
$=$ layer 3	186 (70%)	48 (18%)	31 (12%)
$\leq$ layer 2	114 (43%)	96 (36%)	55 (21%)

- Funding for ns-2 development dropped in the early 2000's

What is wrong about ns-2 ?

- Split object model (OTcl and C++) and use of Tcl:
  - Doesn't scale well
  - Makes it difficult for students
- Large amount of abstraction at the network layer and below leads to big discontinuities when transitioning from simulation to experiment
- Accretion of unmaintained and incompatible models
- Lack of support for creating methodologically sound simulations
- Lack of, and outdated, documentation
- In ns-2, *validation* really means *regression*: no documented validation of the models, outside of TCP

Overheard on e2e-interest mailing list

September 2005 archives of the e2e-interest mailing list:

- “...Tragedy of the Commons...”
- “...around 50% of the papers appeared to be... bogus...”
- “Who has ever validated NS2 code?”
- “To be honest, I’m still not sure whether I will use a simulation in a paper.”
- “...I will have a hard time accepting or advocating the use of NS-2 or any other simulation tool”

A recurring misconception

- Using ns-2 is actively harmful

A recurring misconception

- Using ns-2 is actively harmful

- Simulation is ns-2

A recurring misconception

- Using ns-2 is actively harmful

- Simulation is ns-2

Thus, simulation is actively harmful

Back in 2000's, the rise of testbeds

- Hardware costs going down
- OS virtualization going up
- Development of control and management software

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- Hardware costs going down
- OS virtualization going up
- Development of control and management software

Result:

- Emulab: http://www.emulab.net
- ORBIT: http://www.orbit-lab.org
- Planetlab: http://planet-lab.org
- ModelNet: https://modelnet.sysnet.ucsd.edu
- ...

Why do we need simulation at all ?

- Simulation models are not validated
- Simulation model implementations not verified
- No need for validation and verification in testbeds

Why do we need simulation at all ?

- Simulation models are not validated
- Simulation model implementations not verified
- No need for validation and verification in testbeds

However, there are lots of good things about simulation:

- Reproducibility
- Easier to setup, deploy, instrument
- Investigate non-existent systems
- Scalability

But, really, we need both !

We want to get the best from both worlds:

- Simulators: reproducibility, debuggability, ease of setup
- Testbeds: realism

We want an integrated experimentation environment:

- Use each tool separately:
  - Parameter space exploration with simulations
  - More realism with testbeds
- Use both tools together:
  - Simulator for elements of the topology to scale
  - Testbed for other elements to get realism

Summary

We need simulations:

- Easier to use, debug, reproduce than testbeds
- Not constrained by existing hardware/software

We need a special simulator:

- Improves model validation
- Improves model implementation verification
- Allow users to move back and forth between simulation and testbeds

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Starting from ns-2

The biggest reason to start from ns-2 is:

- A large existing userbase
- A large set of existing models

But, we need to address many issues:

- Most existing models lack validation, verification, maintenance
- Bi-language system (C++/tcl) makes debugging complex: removing it would mean dropping backward compatibility
- Core packet data-structure:
  - Inappropriate for emulation
  - Fragmentation unsupported

Re-engineering ns-2 to fix all these issues would make it a new different simulator: we would lose our existing userbase.

Proprietary simulators

There are many of them (google for *network simulator*):

- Opnet
- QualNet
- Shunra
- etc.

But:

- Terms of use
- Very costly for industrial partners or publicly-funded research which cannot get *education* licenses.

Omnetpp

- It was not clear in 2005 it would still be alive in 2009
- Major worries over the bi-language architecture: learning curve, debugging, etc.
- Software structure did not seem to lend itself to the realism we sought.

Not Invented Here

Yes, we did fall prey to that syndrome too:
we thought we could do it better than the others

Outline

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Good debuggability

C++-only simulations: no need to debug two languages at the same time

- ns-3 is a library written in C++
- Simulation programs are C++ executables
- Bindings in Python for python simulations

Long term project lifetime

A open source community:

- An open license (GPLv2)
- All design and implementation discussions in the open on mailing-lists (even flame wars)
- Everyone can (should) become a maintainer

This is critical to allow:

- The project to scale to many models
- The project to last beyond initial seed funding
- Model/implementations reviews in the open:
  Given enough eyeballs, all bugs are shallow

Low cost of model validation

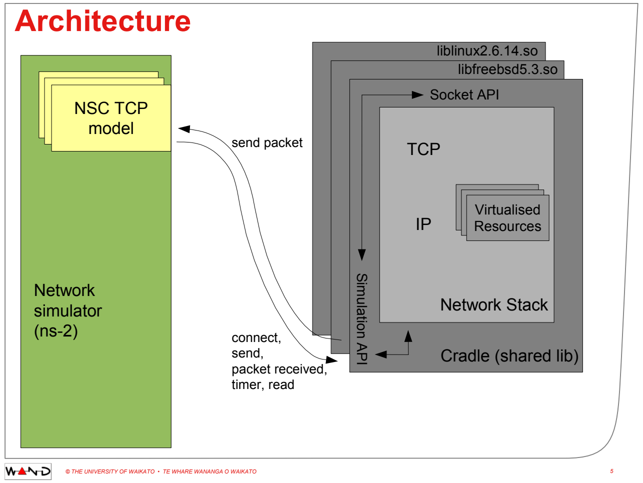
Make models close to the real world:

- Models are less abstract: easier to validate
- Makes it easy to perform direct execution of real code
- Emulation is native and robust against changes in models

How ?

- Real IP addresses
- Multiple interfaces per node
- Bsd-like sockets
- Packets contain real network bytes

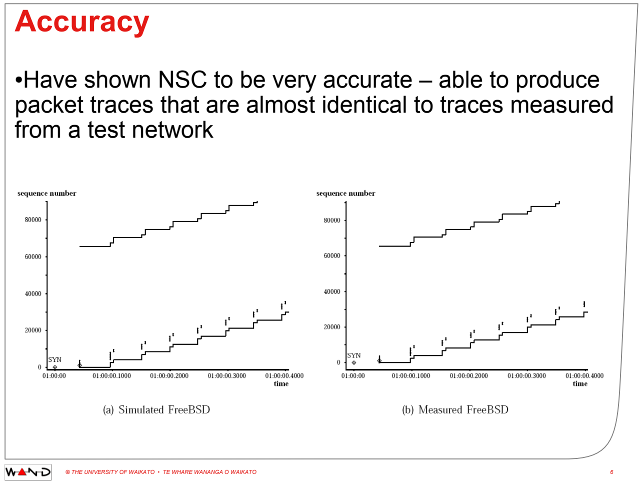
A usecase: NSC



NSC implementation

- Globalizer: per-process kernel source code and add indirection to all global variable declarations and accesses
- Glue: per-kernel (and per-kernel-version) glue to provide kernel APIs for kernel code:
  - kmalloc: memory allocation
  - NetDevice integration
  - Socket integration
- Provides glue for:
  - linux 2.6.18, 2.6.26, 2.6.28
  - FreeBSD 5
  - lwip 1.3
  - OpenBSD 3

NSC accuracy



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

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Summary

ns-3 has a strong focus on realism:

- Makes models closer to the real world: easier to validate
- Allows direct code execution: no model validation
- Allows robust emulation for large-scale and mixed experiments

ns-3 also cares about good software engineering:

- Single-language architecture is more robust in the long term
- Open source community ensures long lifetime to the project

Outline

Things You Should Never Do

It's an old axiom of software engineering:
Don't rewrite from scratch, ever.

We did not really start from scratch:

- Stole code and concepts from *GTNetS* (applications)
- Stole code and concepts from *yans* (wifi)
- Stole code and concepts from *ns-2* (olsr, error models)

Even then, it took us 2 years to get to a useful state

Building an open source community is hard

It's a lot of work to attract contributors and keep them: they want to have fun, they want to have impact on the project:

- Never flame people on mailing-lists:
  - Always answer questions kindly, point out manuals and FAQ
  - Don't answer provocative statements
  - English is not the native language of most users
- We need to do the boring work (release management, bug tracking, server maintenance)
- No discussion *behind closed doors*: increases communication cost
- It's a meritocracy: those who contribute the most should have power to decide for the project

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Need for integrated statistical tools

Initially, we thought we could:

- Allow users to easily instrument the system
- Delegate analysis to third-party tools such as *R*

It does not work that way though:

- Lack of methodology documentation
- Fancy statistical tools are too complex for most users

Future work: integrate tools to automatically measure and improve confidence intervals on simulation output

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Need for a high-level experimentation environment

ns-3 provides low-level functionality:

- Tap devices
- Realtime simulation core

But we want to allow easy switching and mixing of simulation and testbeds. We need higher-level abstractions for:

- Experiment description (topology, application traffic)
- Experiment configuration
- Tracing configuration
- Deployment automation

Work towards this is underway with NEPI (ROADS'09: *NEPI: Using Independent Simulators, Emulators, and Testbeds for Easy Experimentation*: http://www-sop.inria.fr/members/Mathieu.Lacage/roads09-nepi.pdf)

Need for more direct code execution I

Integrate normal POSIX network applications in the simulator:

- No source code modifications
- Easy to debug (great network application development platform !)

Needs:

- Globalization: global variables must be virtualized for each instance of the application running in the simulator
- Filesystem virtualization: each application needs a separate filesystem (to get different configuration and log files for example)
- Socket library: need a complete implementation of sockets in the simulator, including all the crazy ioctls

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Need for more direct code execution II

Status:

- Running demonstrations with ping, traceroute
- Simple socket applications can run: a couple of threads, select, tcp server/client
- Larger applications using fancy socket ioctls don't work very well yet

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Part II

The ns-3 architecture

Outline

Outline

Introduction

Fundamental network model structure

Topology construction

Environment setup

Install all needed tools:

Ubuntu

```
sudo apt-get install build-essential g++ python mercurial
```

Windows

- cygwin
- python
- mercurial

Getting ns-3

Availability (linux, osx, cygwin, mingw):

- Released tarballs: http://www.nsnam.org/releases
- Development version: http://code.nsnam.org/ns-3-dev

The development version is usually stable: a lot of people use it for daily work:

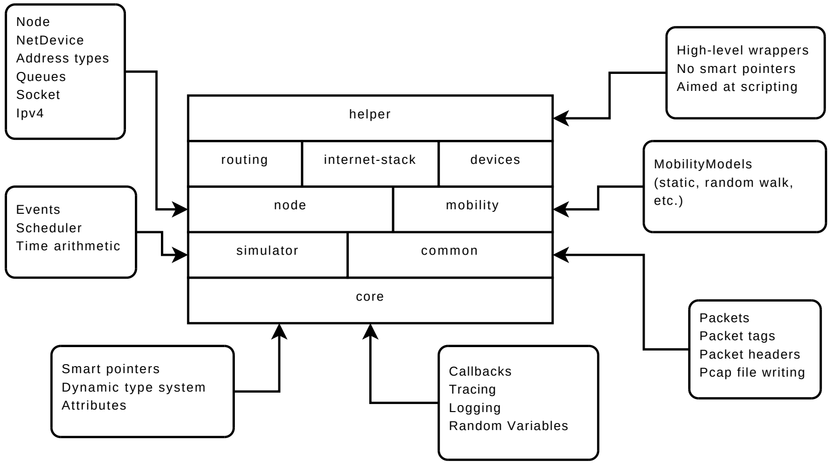
```
hg clone http://code.nsnam.org/ns-3-dev
```

Running ns-3

Use waf to build it (similar to make):

```
./waf
./waf shell
./build/debug/examples/csma-broadcast
```

Exploring the source code



Node
NetDevice
Address types
Queues
Socket
Ipv4

Events
Scheduler
Time arithmetic

helper

routing
internet-stack
devices

node
mobility

simulator
common

core

High-level wrappers
No smart pointers
Aimed at scripting

MobilityModels
(static, random walk, etc.)

Packets
Packet tags
Packet headers
Pcap file writing

Smart pointers
Dynamic type system
Attributes

Callbacks
Tracing
Logging
Random Variables

A typical simulation

- Create a bunch of C++ objects
- Configure and interconnect them
- Each object creates events with Simulator::Schedule
- Call Simulator::Run to execute all events

A (fictional) simulation

```
Node *a = new Node ();
Node *b = new Node ();
Link *link = new Link (a,b);
Simulator::Schedule (Seconds (0.5),              // in 0.5s from now
                     &Node::StartCbr, a,          // call StartCbr on 'a'
                     "100bytes", "0.2ms", b);  // pass these arguments
Simulator::Run ();
```

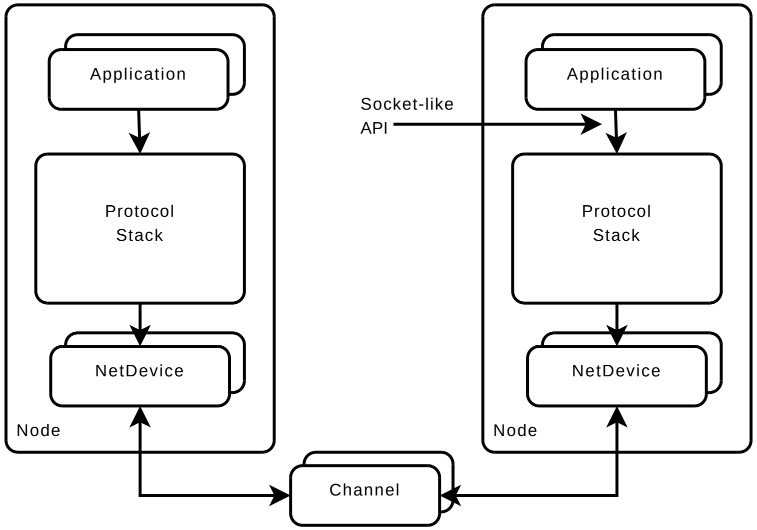
Outline

Introduction

Fundamental network model structure

Topology construction

The basic model



Application
Protocol Stack
NetDevice
Node

Socket-like API

Application
Protocol Stack
NetDevice
Node

Channel

The fundamental objects

- Node: the motherboard of a computer with RAM, CPU, and, IO interfaces
- Application: a packet generator and consumer which can run on a Node and talk to a set of network *stacks*
- Socket: the interface between an application and a network stack
- NetDevice: a network card which can be plugged in an IO interface of a Node
- Channel: a physical connector between a set of NetDevice objects

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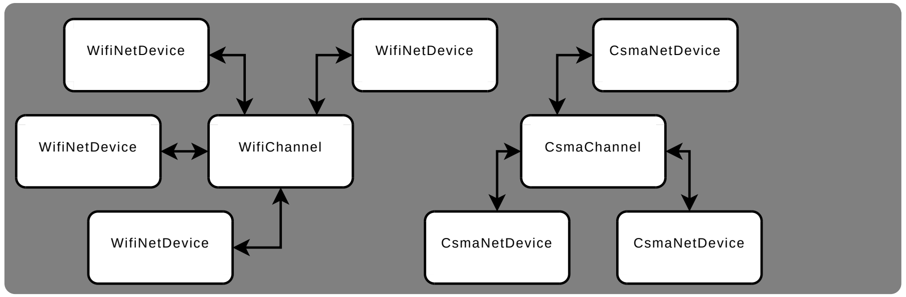
Important remark

NetDevices are strongly bound to Channels of a matching type:



Existing models

- Network stacks: arp, ipv4, icmpv4, udp, tcp (ipv6 under review)
- Devices: wifi, csma, point-to-point, bridge
- Error models and queues
- Applications: udp echo, on/off, sink
- Mobility models: random walk, etc.
- Routing: olsr, static global

For example, the wifi models

- New model, written from 802.11 specification
- Accurate model of the MAC
- DCF, beacon generation, probing, association
- A set of rate control algorithms (ARF, ideal, AARF, Minstrel, etc.)
- Not-so-slow models of the 802.11a PHY

Development of wifi models

New contributions from many developers:

- University of Florence: 802.11n, EDCA, frame aggregation, block ack
- Russian Academy of Sciences: 802.11s, HWMP routing protocol
- Boeing: 802.11b channel models, validation
- Deutsche Telekom Laboratories: PHY modelization, validation
- Karlsruhe Institute of Technology: PHY modelization (Rayleigh, Nakagami)

Summary

- Core models are based on well-known abstractions: sockets, devices, etc.

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- Core models are based on well-known abstractions: sockets, devices, etc.
- An active community of contributors

Outline

The Helper/Container API

We want to:

- Make it easy to build topologies with repeating patterns
- Make the topology description more high-level (and less verbose) to make it easier to read and understand

The idea is simple:

- Sets of objects are stored in Containers
- One operation is encoded in a Helper object and applies on a Container

Helper operations:

- Are not generic: different helpers provide different operations
- Do not try to allow code reuse: just try to minimize the amount of code written
- Provide *syntactical sugar*: make the code easier to read

Typical containers and helpers

Example containers:

- NodeContainer
- NetDeviceContainer
- Ipv4AddressContainer

Example helper classes:

- InternetStackHelper
- WifiHelper
- MobilityHelper
- OlsrHelper
- etc. Each model provides a helper class

Create a couple of nodes

```
NodeContainer csmaNodes;
csmaNodes.Create (2);
NodeContainer wifiNodes;
wifiNodes.Add (csmaNodes.Get (1));
wifiNodes.Create (3);
```

Create empty node container
Create two nodes
Create empty node container
Add existing node to it
And then create some more nodes

Then, the csma network

```
NetDeviceContainer csmaDevices;
CsmaHelper csma;
csma.SetChannelAttribute ("DataRate",
          StringValue ("5Mbps"));
csma.SetChannelAttribute ("Delay",
          StringValue ("2ms"));
csmaDevices = csma.Install (csmaNodes);
```

Create empty device container
Create csma helper
Set data rate

Set delay

Create csma devices and channel

And a couple of wifi interfaces

Finally, setup the wifi channel:

```
YansWifiChannelHelper wifiChannel = YansWifiChannelHelper::Default ();
YansWifiPhyHelper wifiPhy = YansWifiPhyHelper::Default ();
wifiPhy.SetChannel (wifiChannel.Create ());
```

And create adhoc devices on this channel:

```
NetDeviceContainer wifiDevices;
WifiHelper wifi = WifiHelper::Default ();
wifiDevices = wifi.Install (wifiPhy, wifiNodes);
```

Comparison with low-level version

Fire up editor for `tutorial-helper.cc` and `tutorial-lowlevel.cc`

Summary

- It's always possible to create objects by hand, interconnect and configure them

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- But it can be easier to reuse the for loops encapsulated in Helper classes

Summary

- It's always possible to create objects by hand, interconnect and configure them
- But it can be easier to reuse the for loops encapsulated in Helper classes
- Helper classes make scripts less cluttered and easier to read and modify

---

Part III

The ns-3 object model

Outline

It's easy to build a network simulator

It's just a matter of:

- Provide an event scheduler
- Implement a couple of models to create and consume events

But it's much harder to build a network simulator which:

- Allows models to be reusable independently
- Ensures API coherence between models
- Automates common tasks (tracing, configuration)

Outline

A coherent memory management scheme

Maximizing model reuse

Getting the right object

A uniform configuration system

Controlling trace output format

The underlying type metadata database

Why are objects so complicated to create ?

We do:

```
Ptr<Node> node0 = CreateObject<Node> ();
```

Why not:

```
Node *node0 = new Node ();
```

Or:

```
Node node0 = Node ();
```

Templates: the Nasty Brackets

- Contain a list of *type* arguments
- Parameterize a class or function from input type
- In ns-3, used for:
  - Standard Template Library
  - Syntactical sugar for low-level facilities
- Saves a lot of typing
- No portability/compiler support problem
- Sometimes painful to decipher error messages.

Memory Management

It is hard in C++:

- No garbage collector
- Easy to forget to delete an object
- Pointer cycles
- Ensure coherency and uniformity

So, we use:

- Reference counting: track number of pointers to an object (Ref+Unref)
- Smart pointers: Ptr<>, Create<> and, CreateObject<>
- Sometimes, explicit Dispose to break cycles

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Where is my MobileNode ?

```
Ptr<Node> node = CreateObject<Node> ();
Ptr<MobilityModel> mobility = CreateObject<...> ();
node->AggregateObject (mobility);
```

- Some nodes need an IPv4 stack, a position, an energy model.
- Some nodes need just two out of three.
- Others need other unknown features.
- The obvious solution: add everything to the Node base class:
  - The class will grow uncontrollably over time
  - Everyone will need to patch the class
  - Slowly, every piece of code will depend on every other piece of code (cannot reuse anything without dragging in everything)
  - A maintenance nightmare...
- A better solution:
  - Separate functionality belongs to separate classes
  - Objects can be aggregated at runtime to obtain extra functionality

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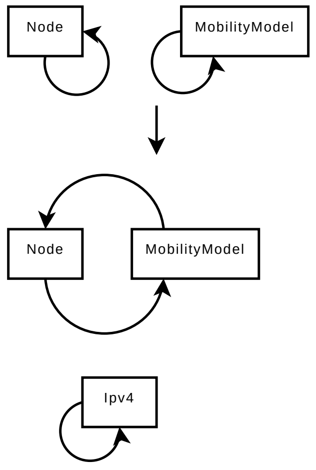
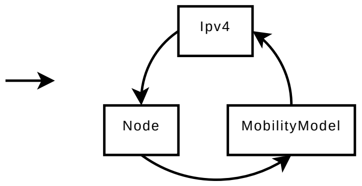
Object aggregation



- A circular singly linked-list
- AggregateObject is a constant-time operation
- GetObject is a O(n) operation
- Aggregate contains only one object of each type



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The traditional approach

In C++, if you want to call methods on an object, you need a pointer to this object. To get a pointer, you need to:

- keep local copies of pointers to every object you create
- walk pointer chains to get access to objects created within other objects

For example, in ns-3, you could do this:

```
Ptr<NetDevice> dev = NodeList::Get (5)->GetDevice (0);
Ptr<WifiNetDevice> wifi = dev->GetObject<WifiNetDevice> ();
Ptr<WifiPhy> phy = dev->GetPhy ();
phy->SetAttribute ("TxGain", ...);
phy->ConnectTraceSource (...);
```

It's not fun to do...

Use a namespace string !

Set an attribute:

```
Config::SetAttribute ("/NodeList/5/DeviceList/0/Phy/TxGain",
                      StringValue ("10"));
```

Connect a trace sink to a trace source:

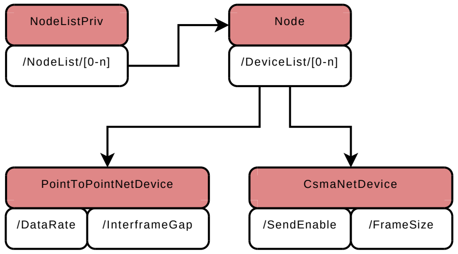
```
Config::Connect ("/NodeList/5/DeviceList/0/Phy/TxGain",
                 MakeCallback (&LocalSink));
```

Just get a pointer:

```
Config::MatchContainer match;
match = Config::LookupMatches ("/NodeList/5/DeviceList/0/Phy/");
Ptr<WifiPhy> phy = match.Get (0)->GetObject<WifiPhy> ();
```

The object namespace I

Object namespace strings represent a path through a set of object pointers:



For example, /NodeList/x/DeviceList/y/InterframeGap represents the InterframeGap attribute of the device number *y* in node number *x*.

The object namespace II

Navigating the attributes using paths:

- /NodeList/[3-5]|8|[0-1]: matches nodes index 0, 1, 3, 4, 5, 8
- /NodeList/*: matches all nodes
- /NodeList/3/$ns3::Ipv4: matches object of type ns3::Ipv4 aggregated to node number 3
- /NodeList/3/DeviceList/*/$ns3::CsmaNetDevice: matches all devices of type ns3::CsmaNetDevice within node number 3
- /NodeList/3/DeviceList/0/RemoteStationManager: matches the object pointed to by attribute RemoteStationManager in device 0 in node 3.

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Traditionally, in C++

- Export attributes as part of a class's public API
- Use static variables for defaults

For example:

```
class MyModel {
public:
  MyModel () : m_foo (m_defaultFoo) {}
  void SetFoo (int foo) {m_foo = foo;}
  int GetFoo (void) {return m_foo}
  static void SetDefaultFoo (int foo) {m_defaultFoo = foo;}
  static int GetDefaultFoo (void) {return m_defaultFoo;}
private:
  int m_foo;
  static int m_defaultFoo = 10;
};
```

In ns-3, done automatically I

- Set a default value:

```
Config::SetDefaultValue ("ns3::WifiPhy::TxGain", StringValue ("10"));
```

- Set a value on a specific object:

```
phy->SetAttribute ("TxGain", StringValue ("10"));
```

- Set a value from the command-line –ns3::WifiPhy::TxGain=10:

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

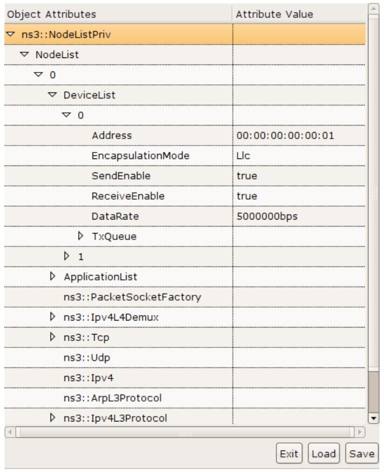
In ns-3, done automatically II

- Load, Change, and Save all values from and to a raw text or xml file with or without a GUI:

```
GtkConfigStore config;
config.ConfigureDefaults ();
...
config.ConfigureAttributes ();
```

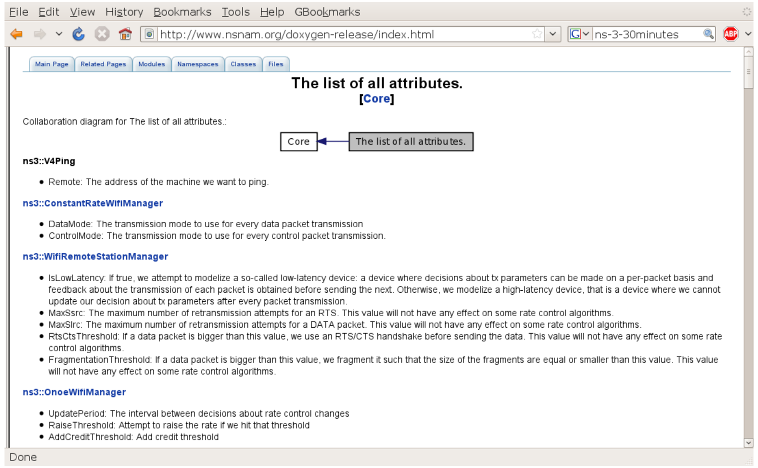
- Set a value with an environment variable
  NS_ATTRIBUTE_DEFAULT=ns3::WifiPhy::TxGain=10

Graphical navigation



Object Attributes	Attribute Value
ns3::NodeListPriv	
NodeList	
0	
DeviceList	
0	
Address	00:00:00:00:00:01
EncapsulationMode	Llc
SendEnable	true
ReceiveEnable	true
DataRate	5000000bps
TxQueue	
1	
ApplicationList	
ns3::PacketSocketFactory	
ns3::Ipv4L4Demux	
ns3::Tcp	
ns3::Udp	
ns3::Ipv4	
ns3::ArpL3Protocol	
ns3::Ipv4L3Protocol	

Doxygen documentation



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.
- FragmentationThreshold: If a data packet is bigger than this value, we fragment it such that the size of the fragments are equal or smaller than this value. This value will not have any effect on some rate control algorithms.

ns3::OnoeWifiManager

- UpdatePeriod: The interval between decisions about rate control changes
- RaiseThreshold: Attempt to raise the rate if we hit that threshold
- AddCreditThreshold: Add credit threshold

Outline

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Tracing requirements

- 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
```

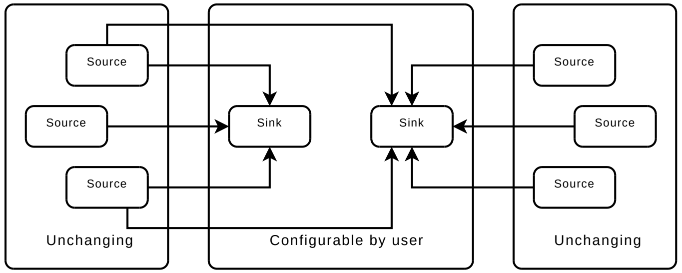
- Problem: tracing needs vary widely
  - Would like to change tracing output format without editing the core
  - Would like to support multiple output formats

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

The ns-3 tracing model

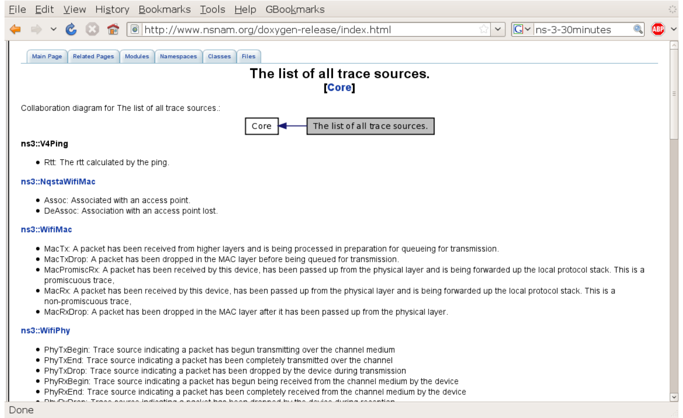
Decouple trace sources from trace sinks:



Benefit: Customizable trace sinks

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



The list of all trace sources.
[Core]

Collaboration diagram for The list of all trace sources.:

ns3::V4Ping

- Rtt: The rtt calculated by the ping.

ns3::NqstaWifiMac

- Assoc: Associated with an access point.
- DeAssoc: Association with an access point lost.

ns3::WifiMac

- MacTx: A packet has been received from higher layers and is being processed in preparation for queueing for transmission.
- MacTxDrop: A packet has been dropped in the MAC layer before being queued for transmission.
- MacPromiscRx: A packet has been received by this device, has been passed up from the physical layer and is being forwarded up the local protocol stack. This is a promiscuous trace,
- MacRx: A packet has been received by this device, has been passed up from the physical layer and is being forwarded up the local protocol stack. This is a non-promiscuous trace,
- MacRxDrop: A packet has been dropped in the MAC layer after it has been passed up from the physical layer.

ns3::WifiPhy

- PhyTxBegin: Trace source indicating a packet has begun transmitting over the channel medium
- PhyTxEnd: Trace source indicating a packet has been completely transmitted over the channel
- PhyTxDrop: Trace source indicating a packet has been dropped by the device during transmission
- PhyRxBegin: Trace source indicating a packet has begun being received from the channel medium by the device
- PhyRxEnd: Trace source indicating a packet has been completely received from the channel medium by the device

---

Multiple levels of tracing

- High-level: use a helper to hook a predefined trace sink to a trace source and generate simple tracing output (ascii, pcap)
- Mid-level: hook a special trace sink to an existing trace source to generate adhoc tracing
- Low-level: add a new trace source and connect it to a special trace sink

High-level tracing

- Use predefined trace sinks in helpers
- All helpers provide ascii and pcap trace sinks

```
CsmaHelper::EnablePcap ("filename", nodeid, deviceid);
std::ofstream os;
os.open ("filename.tr");
CsmaHelper::EnableAscii (os, nodeid, deviceid);
```

Mid-level tracing

- Provide a new trace sink
- Use attribute/trace namespace to connect trace sink and source

```
void
DevTxTrace (std::string context,
          Ptr<const Packet> p, Mac48Address address)
{
  std::cout << " TX to=" << address << " p: " << *p << std::endl;
}
Config::Connect ("/NodeList/*/DeviceList/*/Mac/MacTx",
              MakeCallback (&DevTxTrace));
```

Pcap output

The trace sink:

```
static void PcapSnifferEvent (Ptr<PcapWriter> writer,
                              Ptr<const Packet> packet)
{
  writer->WritePacket (packet);
}
```

Prepare the pcap output:

```
oss << filename << "-" << nodeid << "-" << deviceid << ".pcap";
Ptr<PcapWriter> pcap = ::ns3::Create<PcapWriter> ();
pcap->Open (oss.str ());
pcap->WriteWifiHeader ();
```

Finally, connect the trace sink to the trace source:

```
oss << "/NodeList/" << nodeid << "/DeviceList/" << deviceid;
oss << "/$ns3::WifiNetDevice/Phy/PromiscSniffer";
Config::ConnectWithoutContext (oss.str (),
              MakeBoundCallback (&PcapSnifferEvent, pcap));
```

Outline

A coherent memory management scheme

Maximizing model reuse

Getting the right object

A uniform configuration system

Controlling trace output format

The underlying type metadata database

The ns-3 type system

- The aggregation mechanism needs information about the type of objects at runtime
- The attribute mechanism needs information about the attributes supported by a specific object
- The tracing mechanism needs information about the trace sources supported by a specific object

All this information is stored in `ns3::TypeId`:

- The parent type
- The name of the type
- The list of attributes (their name, their type, etc.)
- The list of trace sources (their name, their type, etc.)

The ns-3 type system

It is not very complicated to use:

- Derive from the `ns3::Object` base class
- Define a `GetTypeId` static method:

```
class Foo : public Object {
public:
  static TypeId GetTypeId (void);
};
```

- Define the features of your object:

```
  static TypeId tid = TypeId ("ns3::Foo")
    .SetParent<Object> ()
    .AddAttribute ("Name", "Help", ...)
    .AddTraceSource ("Name", "Help", ...);
  return tid;
```

- call `NS_OBJECT_ENSURE_REGISTERED`

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Summary

- Simulation is a key component of network research
  - Debuggability
  - Reproducibility
  - Parameter exploration
  - No dependency on existing hardware/software
- ns-3 has a strong focus on realism:
  - Makes models closer to the real world: easier to validate
  - Allows direct code execution: no model validation
  - Allows robust emulation for large-scale and mixed experiments
- ns-3 also cares about good software engineering:
  - Single-language architecture is more robust in the long term
  - Open source community ensures long lifetime to the project

---

Resources

- Web site: http://www.nsnam.org
- Developer mailing list: http://mailman.isi.edu/mailman/listinfo/ns-developers
- User mailing list: http://groups.google.com/group/ns-3-users
- IRC: #ns-3 at irc.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

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