

# Networks Simulation

## Corso di Tecnologie di Infrastrutture di Reti

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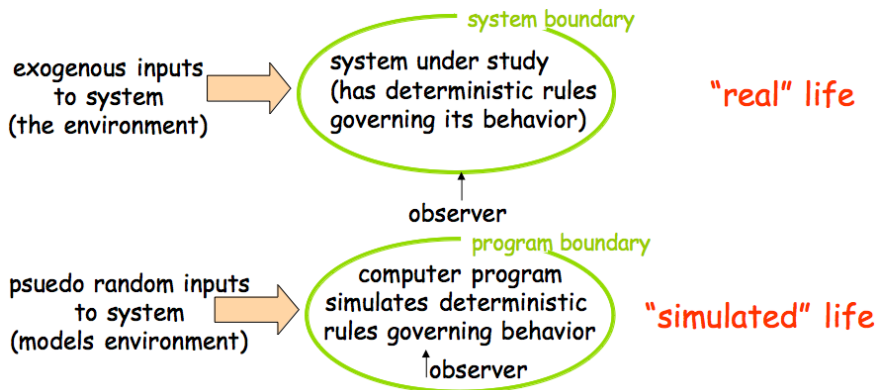


UNIVERSITÀ DEGLI STUDI  
DI MODENA E REGGIO EMILIA

Modena, 26 April 2017

- Motivations
  - What is Simulation
  - Why does it matter?
  - What is Emulation
- Different Simulators
  - Why ns-3 is better?
- Inside ns-3
- Demo/Tutorial

# Simulation in a nutshell



# Why simulation

- Real-system not *available*:
  - complexity (e.g. huge networks);
  - cost (e.g. space communications, satellite);
  - dangerous (e.g. PPDR systems, emergency networks).
- Quick *alternatives* evaluation:
  - star/mesh topology;
  - TCP or UDP for an App;
  - WiMAX or LTE connection;
  - ...
- Evaluate *complex* analytical models (optimal formula unavailable):
  - different QoS solutions;
  - optimizations routing problem for IoT;
  - access techniques for challenging environments;
  - ...

# Simulation: Pros and Cons

- Pros
  - cheaper: quite always;
  - find bugs in advance;
  - generality: over numerical techniques, over topology, ...;
  - detail: tuning the granularity of system details.
- Cons
  - accuracy: does the system reflects reality?;
  - large scale system: lot of resources to simulation;
  - may be slow: (computationally expensive, 1 min real time could be hours of simulated time).

## What's in a simulation program?

- ***simulated time***: internal variable that keeps track of simulated time (could be faster or slower than real time);
- ***system “state”***: variables maintained by simulation program; it defines the system “stat” (e.g. track number of packets in queues, current value of TX timer, ...);
- ***events***: points in the time when system changes state:
  - each event has associate *event time* (e.g. enqueue/dequeue event, state changes, ...);
  - model for time between events (probabilistic) caused by external environment.

## Simulation structure:

- simulation program maintains and updates list of future events: the *event list*;
- well defined set of events;
- for each event there is a simulated system action, an update of the event list.

## Inside Simulation: A formal view

$$\text{simulation} : (\mathcal{S}, \mathcal{E}^n) \xrightarrow{f} (\mathcal{S}, \mathcal{E}^m)$$

where:

$\mathcal{S}$  is the *state* space;

$\mathcal{E}$  is the *event* space;

$\mathcal{E}^n = \{ (e_1, e_2, \dots, e_n) \mid e_i \in \mathcal{E}, \forall i \in [1, n] \}$ .

$$\text{simulation}_{\text{step}} : (s, (e_1, \dots, e_n)) \mapsto (s', (e_2, \dots, e_n) \cup (e'_1, \dots, e'_m))$$

where:

$(e_1, \dots, e_n) \in \mathcal{E}^n$  in the current list of event of the system;

$s \in \mathcal{S}$  is the current system state;

$(e_2, \dots, e_n) \cup (e'_1, \dots, e'_m) \in \mathcal{E}^{n+m-1}$  is the new event list of the system;

$s' \in \mathcal{S}$  is the new system state.



**Emulator** is an hw/sw that duplicates the functions of one computer system, so that the emulated behaviour closely resembles the behaviour of the real system.

- Common in gaming (Nintendo game over PC ...);
- A simulation 2.0;
- Real packets over simulated network;
- Simulated packets over real network.

# Models of a Simulator

A list of common models “modelled” by a network simulator ...  
... **what is a network!?**

# Models of a Simulator

A list of common models “modelled” by a network simulator ...

... **what is a network!?**

- **Nodes**

- **Links**

# Models of a Simulator

A list of common models “modelled” by a network simulator ...

... **what is a network!?**

- **Nodes**

- End-system (host)
- Router
- Hub ...

- **Links**

- Ethernet
- Point-to-Point
- Wireless ...

## • Applications

- Bulk TCP transfer (very common)
- TCP/UDP “on-off” application
- Web Browsing
- P2P file transfer
- Video streaming
- VoIP
- Chat ...

## • Protocols

- TCP vs UDP
- IPv4 vs IPv6
- Routing Protocol (BGP, OSPF, ...)

- **Network Interfaces**
  - Wired/Wireless
  - Layer 2 protocol (802.x family)
- **Packets**
  - Real data vs “Dummy”
- **Routers and Queueing**
  - I/O buffers
  - Route lookup delays
  - Routing table representation
  - Queueing techniques

# Output of a Simulator

How to analyse the simulation results?

- **Trace file**

- Log packet receipt/transmit
- Log queue size, drop ...

- **Built-in statistics gathering**

- Link utilization
- Queue occupancy
- Throughput
- Loss rate

- **Custom Tracing**

- User specifies which packets/links/nodes to trace

Who is the best?

- **ns2**
  - Original “design” by Steve McCanne
  - OTcL/C++ hybrid
  - open source
  - De-facto standard in academic research (last decade)
- **Georgia Tech Network Simulator (GTNetS)**
  - Completely C++
  - Designed for distributed simulation (scalable)
  - BGP model



- **OPNET**
  - Commercial, closed source tool
  - De-facto standard in Military (cash!)
  - Full-Featured, nice GUI
  - Fine-grained data analysis feature
- **QualNet**
  - Commercial, closed source tool
  - Competes primarily with OPNET
  - Strong in Wireless models

- **SSFNet**
  - Both Java and C++ versions
  - Designed for “parallel” simulations (multiCore, not distributed)
- **OMNet++**
  - C++ engine
  - Common in European Community
- **MiniNet**
  - Python models
  - Used by the SDN community (OpenFlow paradigm)
  - Full Emulator

## Network Simulator 3

discrete-event network simulator for  
Internet systems



- Partially founded by US NSF grant
- Large Community (Investigators, Programmer, Staff, Volunteers)
- Modular and Scalable software
- Abstraction and Realism (Accurate!)
- Integration, between emulation
- Lot of Modules (WiFi, cellular, ...)
- Education (examples, tutorials, projects, courses)
- Maintenance (validations, documentation, distribution)

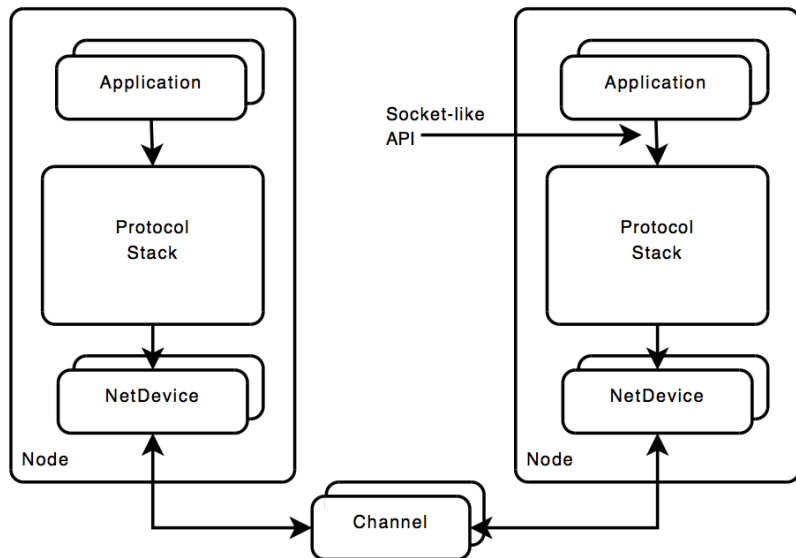


- Flexible event scheduler
- Output traces in ascii or Pcap (readable with WireShark)
- Emulation mode
  - Integration with real networks or real packets
  - Real-Time Scheduler
- Doxygen documentation
- Mercurial code repo

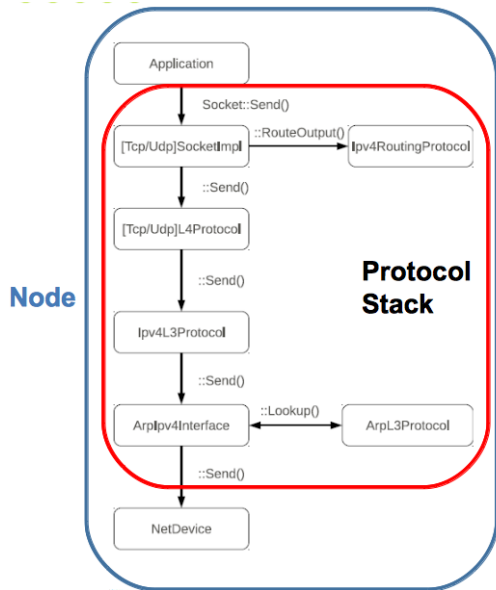


- Use of “smart pointers” to ease memory management
- Use of “Object Aggregation” to allow easy object extension functionality
- Simulation event scheduling on arbitrary functions with arbitrary argument lists
- Packet objects manage sequential array (easy add/remove headers or data)

## ns3 basic model



# ns3 protocol stack



Protocol stack encapsulates:

- TCP sockets
- transport protocol
- network protocol
- routing
- ...

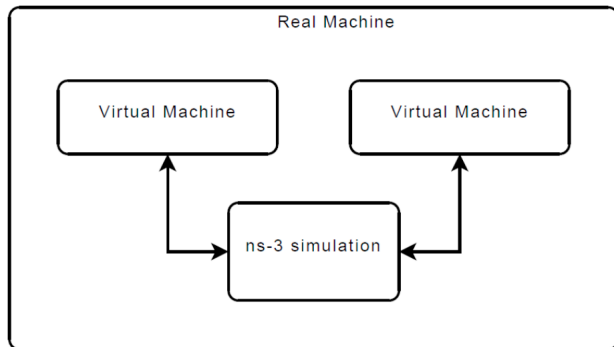
## ns3 current modules

aodv	applications	bridge
click	config-store	core
csma	dama	dsv
emu	energy	flow-monitor
internet	lte	mesh
mobility	mpi	netanim
network	nix-vector-routing	olsr
openflow	point-to-point	point-to-point-layout
propagation	spectrum	stats
tap-bridge	test	tools
topology-read	uan	virtual-net-device
visualizer	wifi	wimax



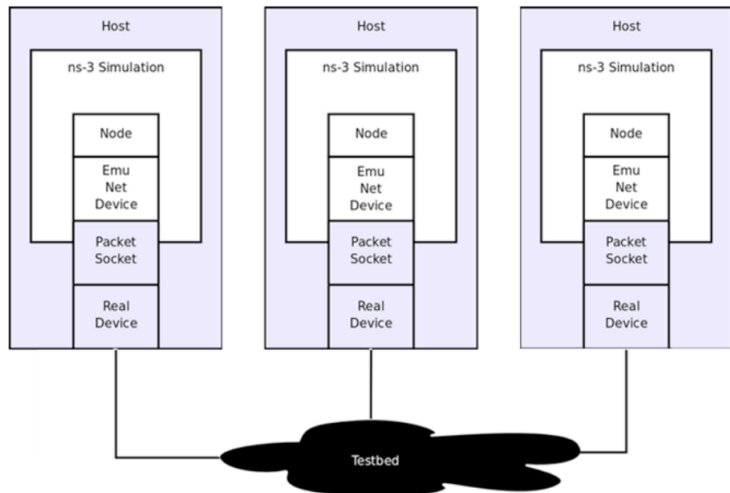
# ns3 emulation 1/2

- Stack : *real*
- Network : *simulated*

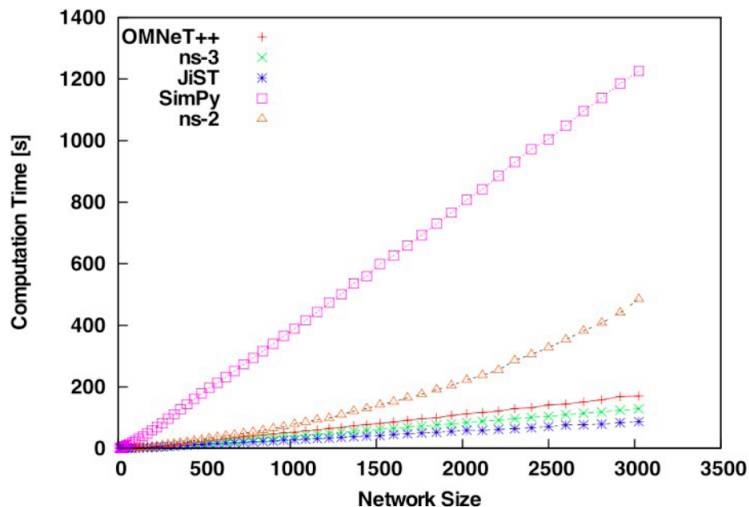


## ns3 emulation 2/2

- Stack : *simulated*
- Network : *real*

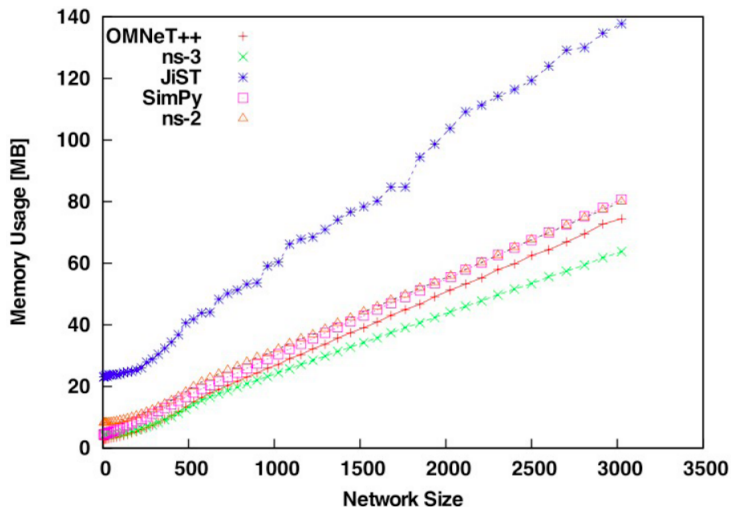


## ns3 time performance



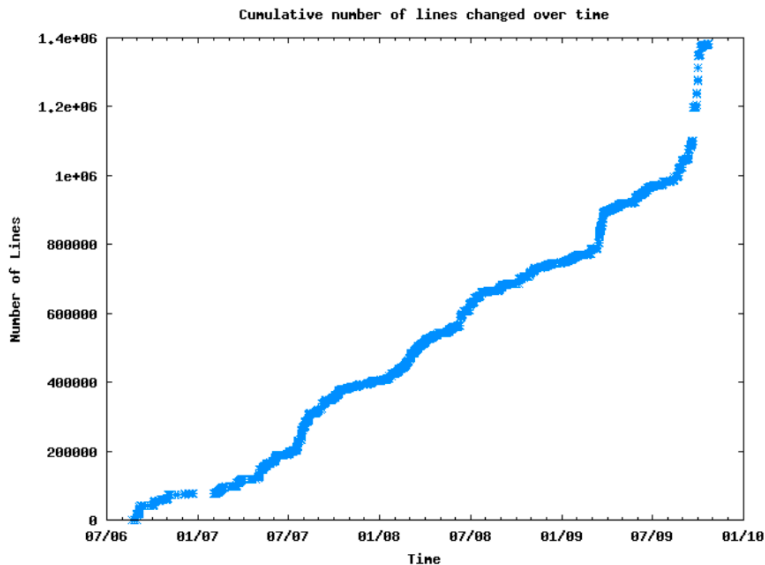
E. Weingartner, H. Lehn, and K. Wehrle, "A performance comparison of recent network simulators", *IEEE ICC*, 2009.

## ns3 memory performance



E. Weingartner, H. Lehn, and K. Wehrle, "A performance comparison of recent network simulators", *IEEE ICC*, 2009.

# ns3 code evolution



# Numbers about ns3

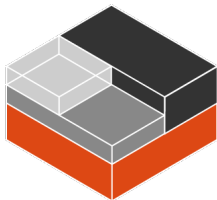
- Line of code:  $\sim 300k$
- Downloads:  $> 50k$ ;
- Subscribed users:  $> 3.5k$ ;
- Developers:  $> 1k$ ;
- Citations:  $> 100k$

## Citations about ns2/ns3

- ns2/ns3 became the main choice for research usage. Source: ACM Digital Library:

	ns2	OPNET	QualNet
$\geq$ 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%)

- nowadays ns3 moves also conferences, workshops, tutorials and GSoC;
- ns3 is currently the standard *de-facto* for research purposes.



LXC

## Tutorial on **NON**-Simulation

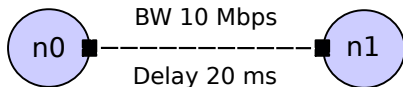
How to perform a **real** TCP connection on a Linux system

Only facing the non-flexibility of a real system we'll understand the usefulness of simulators



# Real TCP Connection on a Real System

We want this:

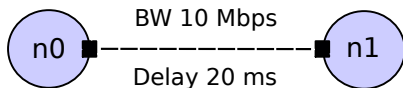


How to run it? We need:

- Two nodes
  - a TCP sender
  - a TCP receiver
- a real (configurable) **link**/connection between the nodes
- something to generate (the desired) TCP **traffic**
- a smart way to **monitor** what's happening on our system

# Real TCP Connection on a Real System

We want this:



Dummy solution:

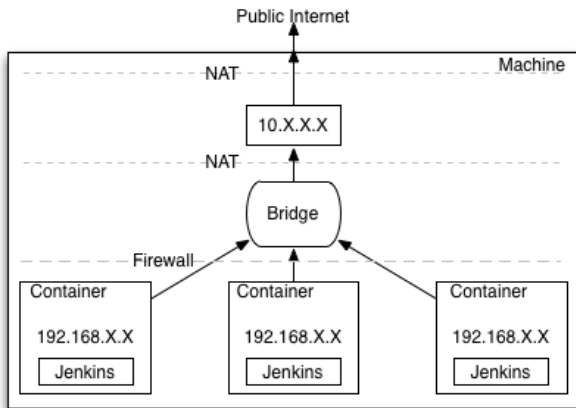
- Buy two laptop
- Buy a 10mbit/s Ethernet long enough to have 20ms of propagation delay (unreal)
- Configure the two laptops in order to communicate through the cable
- Start a specific TCP connection, generate some traffic and analyse it

## First *better* solution:



LXC is a very flexible and easy-to-configure virtual machine well integrated with the main Linux system

## First *better* solution:



We can easily create nodes and let them communicate

First *better* solution:



Install LXC and execute the ex. test: Step-by-step guide

## Install LXC and create two containers: on Ubuntu

Legend: **ms** = main system, **ca** = container a and **cb** = container b.

Open a Terminal:

```
ms$ sudo apt-get install lxc
ms$ sudo lxc-create -t ubuntu -n my-container-a
ms$ sudo lxc-create -t ubuntu -n my-container-b
```

both *my-container-a* and *my-container-b* have the default config with user/pass equal to ubuntu/ubuntu.

Look at the containers status with:

```
ms$ sudo lxc-ls
```

## Move **into** a container (*ca* : container a)

On the main system:

```
ms$ sudo lxc-start -n my-container-a  
ms$ sudo lxc-attach -n my-container-a
```

this command switch environment and we move into a *ca* shell

Look at the connections of *ca* with:

```
ca$ ifconfig
```

we focus on *eth0*, we refer to the ip address of *ca* as *eth0<sub>a</sub>*

## Move **into** a container (*cb* : container b)

On the main system:

```
ms$ sudo lxc-start -n my-container-b  
ms$ sudo lxc-attach -n my-container-b
```

this command switch environment and we move into a *cb* shell

Look at the connections of *cb* with:

```
cb$ ifconfig
```

we focus on *eth0*, we refer to the ip address of *cb* as *eth0<sub>b</sub>*



## Create the TCP connection *ca* -> *cb*

On *cb*, our server:

```
cb$ sudo apt-get install iperf  
cb$ sudo iperf -s
```

On *ca*, our client:

```
ca$ sudo apt-get install iperf  
ca$ sudo iperf -c eth0b -t 5
```

Good news: *ca* -> *cb* works!

## Monitor the connection *ca* -> *cb*

On the main system:

```
ms$ wireshark
```

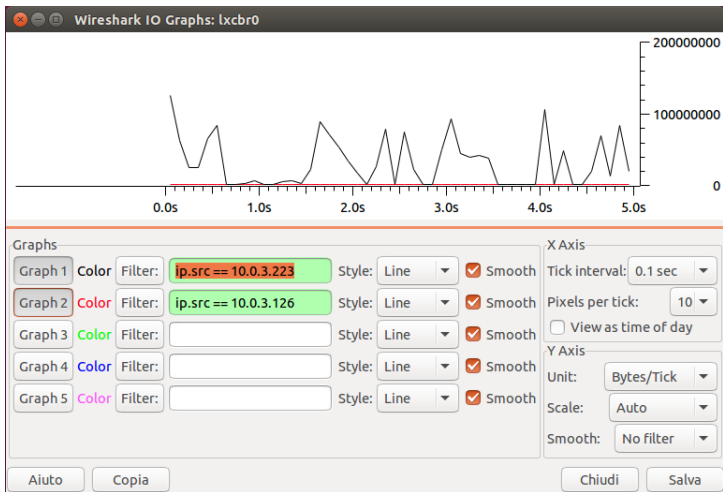
or simply open the program "graphically" by clicking on it

Start to monitor the *lxcbr0* interface, created by the main system immediately after the creation of the first *lxc*. Start again the client *ca*, what you will see is this:

(continue)

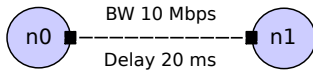
## Monitor the connection *ca* -> *cb*

On WireShark: Statistics -> IO Graph -> done!

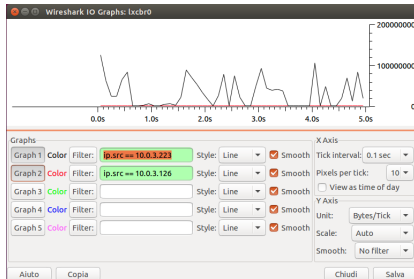


# But remember...

We want this:



But we have this:



## Set BandWidth and Delay on boyth *ca* and *cb*

On the container *ca*:

```
ca$ sudo tc qdisc add dev eth0 handle 1: root htb default 11
ca$ sudo tc class add dev eth0 parent 1: classid 1:1 htb rate 1.25mbps
ca$ sudo tc class add dev eth0 parent 1:1 classid 1:11 htb rate 1.25mbps
ca$ sudo tc qdisc add dev eth0 parent 1:11 handle 10:1 netem delay 20ms
```

do the same on *cb*

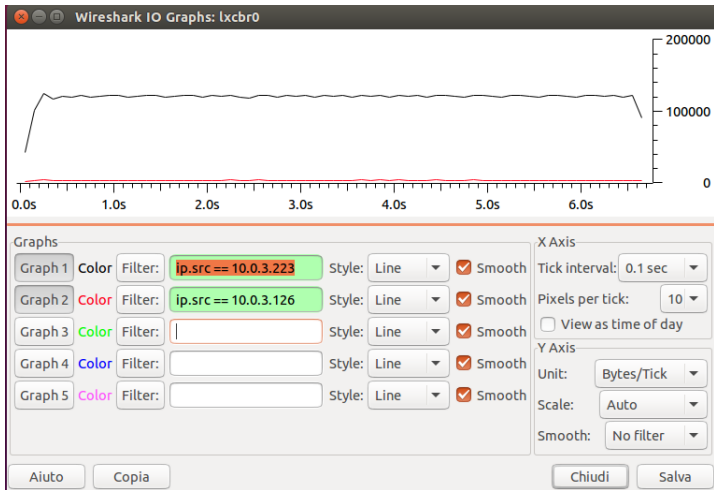
### NOTE

mbps for *tc* tool is MBps actually

painful? not as a **real** system...but if we want more...this is not enough

## Monitor the connection *ca* -> *cb*

Start again Wireshark monitoring *lxcbr0*, start the client *ca* and:





# Tutorial on ns3

## Install and Execute

## Install ns3: Using git as source code manager

On Ubuntu:

```
$ git clone https://github.com/nsnam/ns-3-dev-git.git
$ cd ns-3-dev-git
$ ./waf configure --enable-examples
$ ./waf --run first
```

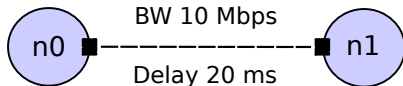
On Mac OSx

```
$ git clone https://github.com/nsnam/ns-3-dev-git.git
$ cd ns-3-dev-git
$ ./waf configure --enable-examples
$ ./waf --run first
```



## Run first example: TCP Bulk

Draft of the example:

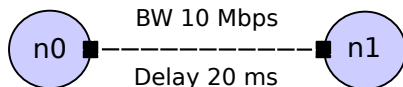


How to run it?

```
$ ./waf --run "tcp-bulk-send --tracing"  
$  
$ cat tcp-bulk-send.tr  
$ tcpdump -tt -r tcp-bulk-send-0-0.pcap  
$ wireshark tcp-bulk-send-0-0.pcap
```

# Learn from first example: TCP Bulk

The goal is:



# Learn from first example: TCP Bulk

Step 0 header and main:

```
#include <string>
#include <fstream>
#include "ns3/core-module.h"
#include "ns3/point-to-point-module.h"
#include "ns3/internet-module.h"
#include "ns3/applications-module.h"
#include "ns3/network-module.h"
#include "ns3/packet-sink.h"

using namespace ns3;

NS_LOG_COMPONENT_DEFINE ("TcpBulkSendExample");

int
main (int argc, char *argv[])
{
    bool tracing = false;
    uint32_t maxBytes = 0;
```

# Learn from first example: TCP Bulk

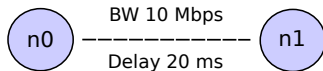
Step 1 create the nodes:



```
//  
// Explicitly create the nodes required by the topology (shown  
// above).  
//  
NS_LOG_INFO ("Create nodes.");  
NodeContainer nodes;  
nodes.Create (2);
```

# Learn from first example: TCP Bulk

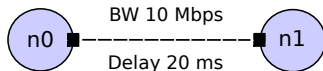
Step 2 create the link:



```
NS_LOG_INFO ("Create channels.");  
//  
// Explicitly create the point-to-point link required by the  
// topology (shown above).  
//  
PointToPointHelper pointToPoint;  
pointToPoint.SetDeviceAttribute ("DataRate", StringValue ("10Mbps  
"));  
pointToPoint.SetChannelAttribute ("Delay", StringValue ("20ms"));
```

# Learn from first example: TCP Bulk

Step 3 connect nodes and link:

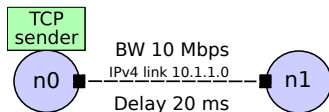


```
NetDeviceContainer devices;  
devices = pointToPoint.Install (nodes);  
//  
// Install the internet stack on the nodes  
//  
InternetStackHelper internet;  
internet.Install (nodes);
```



## Learn from first example: TCP Bulk

Step 5 create the application:

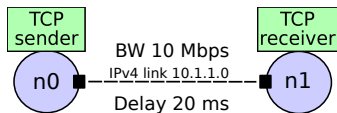


```
NS_LOG_INFO ("Create Applications.");  
//  
// Create a BulkSendApplication and install it on node 0  
//  
uint16_t port = 9; // well-known echo port number  
BulkSendHelper source ("ns3::TcpSocketFactory",  
                       InetAddress (i.GetAddress (1), port)  
                       );  
// Set the amount of data to send in bytes. Zero is unlimited.  
source.SetAttribute ("MaxBytes", UIntegerValue (maxBytes));  
ApplicationContainer sourceApps = source.Install (nodes.Get (0));  
sourceApps.Start (Seconds (0.0));  
sourceApps.Stop (Seconds (5.0));
```



# Learn from first example: TCP Bulk

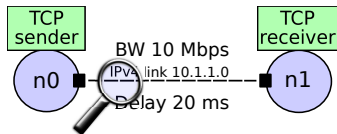
Step 6 create the receiver socket:



```
//  
// Create a PacketSinkApplication and install it on node 1  
//  
PacketSinkHelper sink ("ns3::TcpSocketFactory",  
                       InetSocketAddress (Ipv4Address::GetAny ()  
                                           , port));  
ApplicationContainer sinkApps = sink.Install (nodes.Get (1));  
sinkApps.Start (Seconds (0.0));  
sinkApps.Stop (Seconds (5.0));
```

# Learn from first example: TCP Bulk

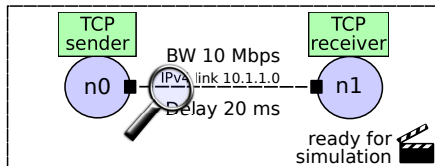
Step 7 set up tracing:



```
//  
// Set up tracing if enabled  
//  
if (tracing)  
{  
    AsciiTraceHelper ascii;  
    pointToPoint.EnableAsciiAll (ascii.CreateFileStream ("tcp-  
        bulk-send.tr"));  
    pointToPoint.EnablePcapAll ("tcp-bulk-send", false);  
}
```

# Learn from first example: TCP Bulk

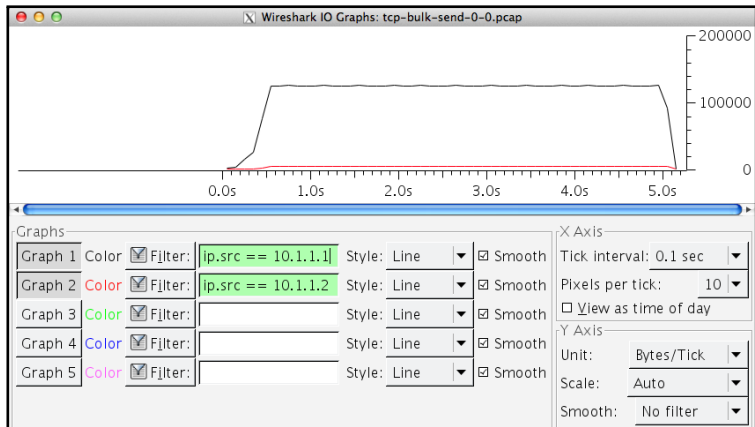
Step 8 actual simulation:



```
//  
// Now, do the actual simulation.  
//  
NS_LOG_INFO ("Run Simulation.");  
Simulator::Stop (Seconds (10.0));  
Simulator::Run ();  
Simulator::Destroy ();  
NS_LOG_INFO ("Done.");
```

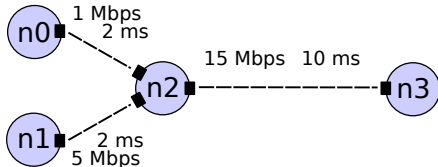
# Demo on TCP Bulk

Pcap analysis of TCP Bulk example with WireShark:



## Run second example: Global Routing

Draft of the example:

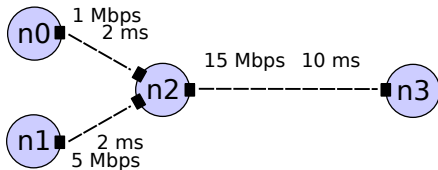


How to run it?

```
$ ./waf --run simple-global-routing  
$  
$ cat simple-global-routing.tr  
$ tcpdump -tt -r simple-global-routing-2-3.pcap  
$ wireshark simple-global-routing-2-3.pcap
```

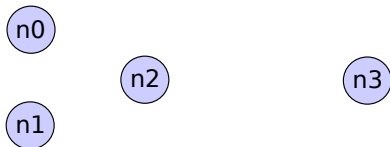
# Learn from second example: Global Routing

The goal is:



## Learn from second example: Global Routing

Step 1 create the nodes:

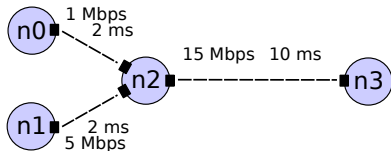


```
// Here, we will explicitly create four nodes. In more
// sophisticated
// topologies, we could configure a node factory.
NS_LOG_INFO ("Create nodes.");
NodeContainer c;
c.Create (4);
NodeContainer n0n2 = NodeContainer (c.Get (0), c.Get (2));
NodeContainer n1n2 = NodeContainer (c.Get (1), c.Get (2));
NodeContainer n3n2 = NodeContainer (c.Get (3), c.Get (2));

InternetStackHelper internet;
internet.Install (c);
```

## Learn from second example: Global Routing

Step 2 create the link:



```
// We create the channels first without any IP addressing
information
NS_LOG_INFO ("Create channels.");
PointToPointHelper p2p;
p2p.SetDeviceAttribute ("DataRate", StringValue ("1Mbps"));
p2p.SetChannelAttribute ("Delay", StringValue ("2ms"));
NetDeviceContainer d0d2 = p2p.Install (n0n2);

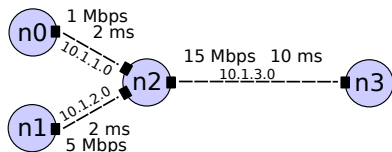
p2p.SetDeviceAttribute ("DataRate", StringValue ("5Mbps"));
NetDeviceContainer d1d2 = p2p.Install (n1n2);

p2p.SetDeviceAttribute ("DataRate", StringValue ("15Mbps"));
p2p.SetChannelAttribute ("Delay", StringValue ("10ms"));
NetDeviceContainer d3d2 = p2p.Install (n3n2);
```



## Learn from second example: Global Routing

Step 3 configure the network:



```
// Later, we add IP addresses.
NS_LOG_INFO ("Assign IP Addresses.");
Ipv4AddressHelper ipv4;
ipv4.SetBase ("10.1.1.0", "255.255.255.0");
Ipv4InterfaceContainer i0i2 = ipv4.Assign (d0d2);

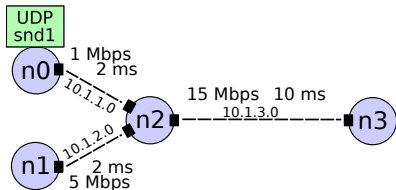
ipv4.SetBase ("10.1.2.0", "255.255.255.0");
Ipv4InterfaceContainer i1i2 = ipv4.Assign (d1d2);

ipv4.SetBase ("10.1.3.0", "255.255.255.0");
Ipv4InterfaceContainer i3i2 = ipv4.Assign (d3d2);

// Create router nodes, initialize routing database and set up
// the routing
// tables in the nodes.
Ipv4GlobalRoutingHelper::PopulateRoutingTables ();
```

## Learn from second example: Global Routing

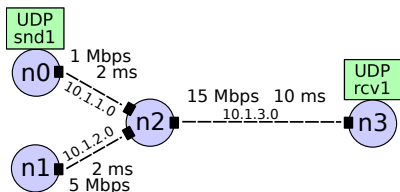
Step 4 create first app sender:



```
// Create the OnOff application to send UDP datagrams of size
// 210 bytes at a rate of 1 Mb/s
NS_LOG_INFO ("Create Applications.");
uint16_t port = 9; // Discard port (RFC 863)
OnOffHelper onoff ("ns3::UdpSocketFactory",
                  Address (InetSocketAddress (i3i2.GetAddress (0),
                                             port)));
onoff.SetConstantRate (DataRate ("1Mb/s"));
ApplicationContainer apps = onoff.Install (c.Get (0));
apps.Start (Seconds (1.0));
apps.Stop (Seconds (10.0));
```

## Learn from second example: Global Routing

Step 5 create first app receiver:

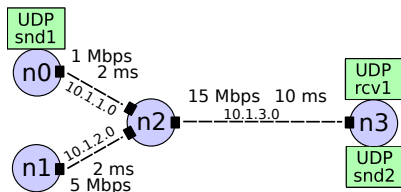


```
// Create a packet sink to receive these packets
PacketSinkHelper sink ("ns3::UdpSocketFactory",
    Address (InetSocketAddress (Ipv4Address::
        GetAny (), port)));

apps = sink.Install (c.Get (3));
apps.Start (Seconds (1.0));
apps.Stop (Seconds (10.0));
```

## Learn from second example: Global Routing

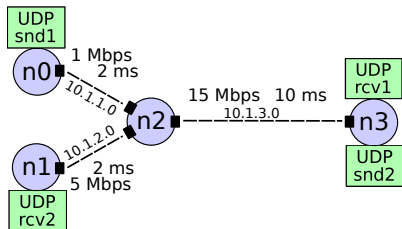
Step 6 create second app sender:



```
// Create a similar flow from n3 to n1, starting at time 1.1
seconds
onoff.SetAttribute ("Remote",
                  AddressValue (InetSocketAddress (i1i2.
                  GetAddress (0), port)));
onoff.SetConstantRate (DataRate ("5Mb/s"));
apps = onoff.Install (c.Get (3));
apps.Start (Seconds (1.1));
apps.Stop (Seconds (10.0));
```

## Learn from second example: Global Routing

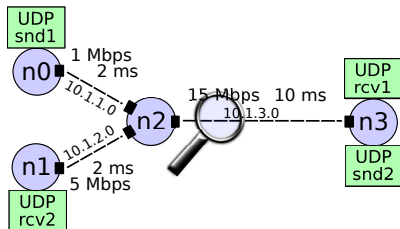
Step 7 create second app receiver:



```
// Create a packet sink to receive these packets
apps = sink.Install (c.Get (1));
apps.Start (Seconds (1.1));
apps.Stop (Seconds (10.0));
```

## Learn from second example: Global Routing

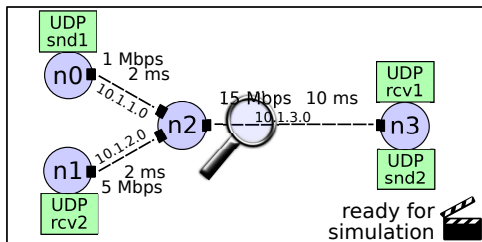
Step 8 set up tracing:



```
AsciiTraceHelper ascii;  
p2p.EnableAsciiAll (ascii.CreateFileStream ("simple-global-  
routing.tr"));  
p2p.EnablePcapAll ("simple-global-routing");
```

## Learn from second example: Global Routing

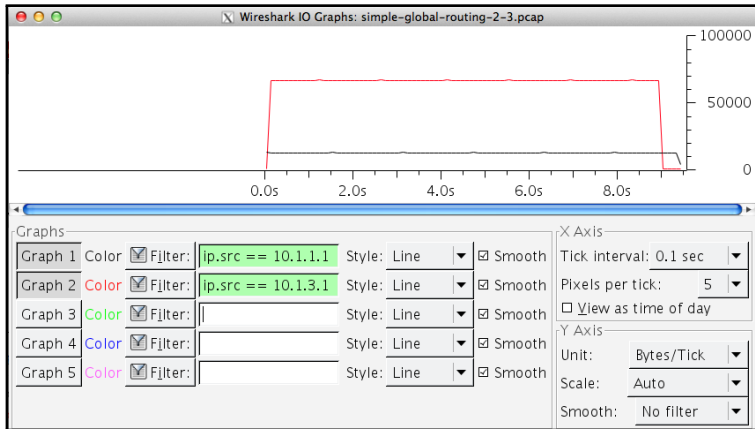
Step 9 actual simulation:



```
NS_LOG_INFO ("Run Simulation.");  
Simulator::Stop (Seconds (12));  
Simulator::Run ();  
NS_LOG_INFO ("Done.");  
Simulator::Destroy ();  
return 0;
```

# Demo on Global Routing

Pcap analysis of Global Routing example with Wireshark:





## Next steps with ns3

- Download it (see slide 46 of this presentation for details)
- Try it (look at the examples of this presentation)
- Play it (tune your own code)
- Do not forget to use WireShark

### Next *practical* lesson: end of the course

- Bring your own laptop (with ns-3 on)
  - you can't? form a group
    - you can't? follow at least. Don't worry
- Follow the lesson actively
- Try to solve some exercises (together)

## Exam Proposals about ns3

- MultiPath-TCP
- TCP variants (like Cubic, default linux TCP)
- Performance measurements
- Narrow time measurement
- Cross-layer message passing
- User mobility study
- AQM algorithms (queueing discipline)

- ns3 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>
- 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](http://www.nsnam.org/wiki/index.php/Main_Page)



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