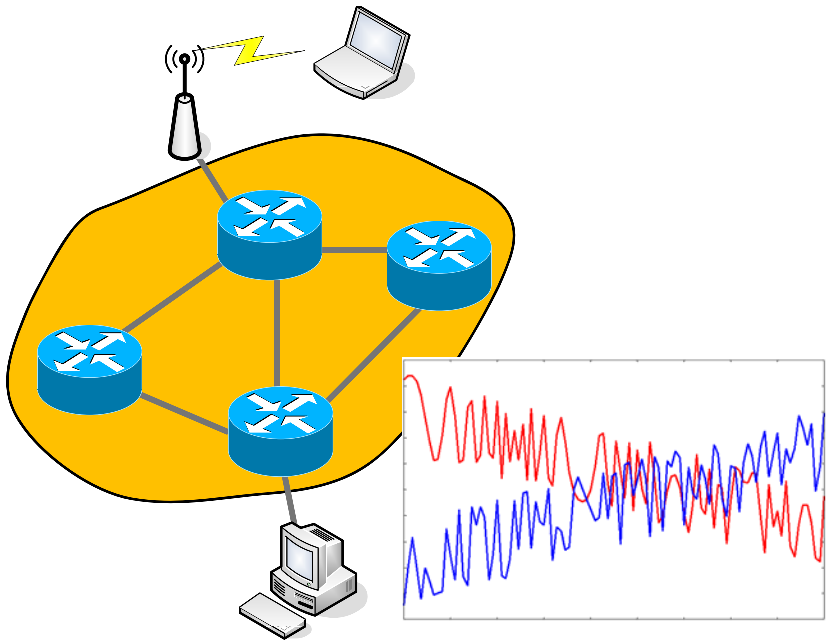
Chapter 4

Introduction to Network Simulators



Contents

- Network Simulation Tools
- ns-2
- OMNeT++

Network Simulation Tools

Network Simulation Tools

- ns-2 Network Simulator
  http://nsnam.isi.edu/nsnam/index.php/Main_Page
  - ns-2 is a discrete event simulator targeted at networking research.
  - ns-2 provides substantial support for simulation of TCP, routing, and multicast protocols over wired and wireless (local and satellite) networks.
  - Successor ns-3: http://www.nsnam.org/wiki/index.php/Main_Page
- OMNeT++
  http://www.omnetpp.org
  - OMNeT++ is an open-source, component-based simulation package built on C++ foundations. It offers a C++ simulation class library and GUI support (graphical network editing, animation).

Network Simulation Tools

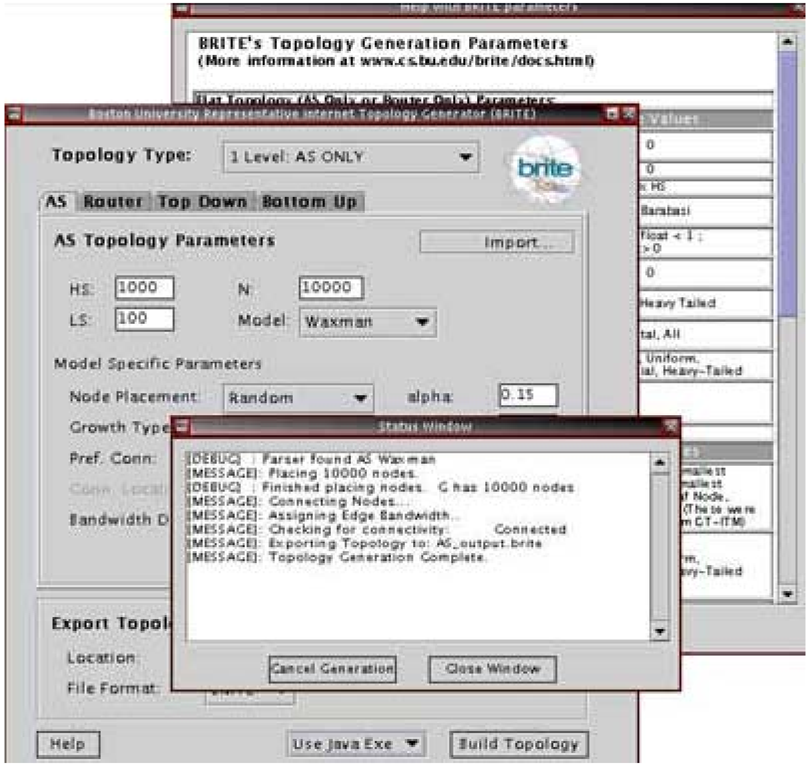
- SSFNet: http://www.ssfnet.org/
  - SSF (Scalable Simulation Framework) is a standard for discrete-event simulation in Java and C++. Several SSF implementations and a large number of open-source protocol models and other components exist.
- Parsec: http://may.cs.ucla.edu/projects/parsec/
  - A C-based simulation language for sequential and parallel execution of discrete-event simulation models
- Scalable Networks (Qualnet): http://www.scalable-networks.com
  - Network simulator designed from the outset for maximum speed and scalability, with real-time simulation as an achievable goal.
- OPNET Modeler: http://www.opnet.com/
  - OPNET Modeler is a commercial tool for modeling and simulation of networks, devices, and protocols. It features graphical editors and animation.

Network Simulation Tools

- JiST/SWANS: http://jist.ece.cornell.edu/
  - "JiST is a high-performance discrete event simulation engine that runs over a standard Java virtual machine. It is a prototype of a new general-purpose approach to building discrete event simulators, called *virtual machine-based simulation*, that unifies the traditional systems and language-based simulator designs. The resulting simulation platform is surprisingly efficient. It out-performs existing highly optimized simulation runtimes both in time and memory consumption. For example, *JiST has twice the raw event throughput of the highly optimized, C-based Parsec engine, and supports process-oriented simulation using a fraction of the memory*."

Network Simulation Tools

- BRITE: http://www.cs.bu.edu/brite/
  - Tool for generation of realistic internet topologies, with export to several network simulators (ns-2, SSFNet, OMNeT++).



Network Simulation Tools

- Akaroa: http://www.cosc.canterbury.ac.nz/research/RG/net_sim/simulation_group/akaroa/
  - Akaroa is a package for supporting the Multiple Replications In Parallel (MRIP) simulation technique to harness the computing power of a network of inexpensive workstations.
  - Integration exists with the ns-2 and OMNeT++ simulators.

The Network Simulator, ns-2

ns-2

- Simple model
  - A discrete event simulator
- Focused on modeling network protocols
  - Wired, wireless, satellite
  - TCP, UDP, multicast, unicast
  - Web, telnet, ftp
  - Ad-hoc routing, sensor networks
  - Infrastructure: stats, tracing, error models, etc.
- Literature
  - Project homepage: http://www.isi.edu/nsnam/
  - Ns manual: http://www.isi.edu/nsnam/ns/ns-documentation.html

ns-2: Goal

- Support networking research and education
  - Protocol design, traffic studies, etc.
  - Protocol comparison
- Provide a collaborative environment
  - Freely distributed, open source
- Share code, protocols, models, etc.
  - Allow easy comparison of similar protocols
  - Increase confidence in results
- More people look at models in more situations
- Experts develop models
- Multiple levels of detail in one simulator

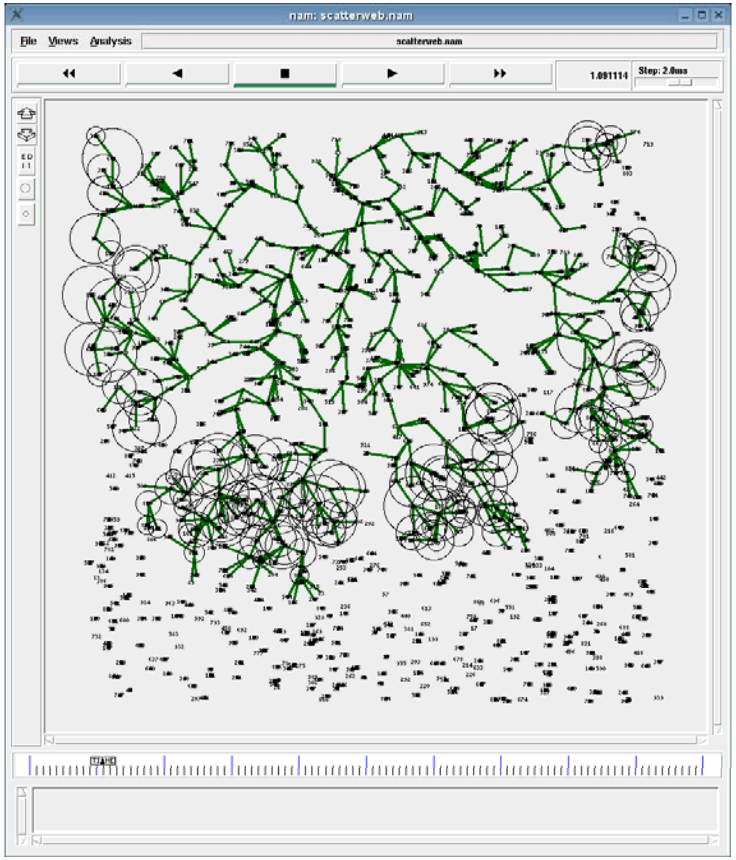
ns-2: History

- Development began as REAL in 1989
- ns by Floyd and McCanne at LBL
- ns-2 by McCanne and the VINT project (LBL, PARC, UCB, USC/ISI)
- Currently maintained at USC/ISI

- In future **ns-3** (http://www.nsnam.org/)
  - "The ns-3 project is developing a discrete-event network simulator for Internet systems, targeted primarily for research and educational use. ns-3 is the next major revision of the ns-2 simulator. The acronym *"nsnam"* derives historically from the concatenation of *ns* (network simulator) and *nam* (network animator)."

ns-2: Components

- ns: the simulator itself
- nam: the Network Animator
  - Visualize ns (or other) output
  - GUI input simple ns scenarios
- Pre-processing:
  - Traffic and topology generators
- Post-processing:
  - Simple trace analysis, often in Awk, Perl, Python, or Tcl



ns-2: Models

- Traffic models and applications
  - Web, FTP, Telnet, Constant-bit Rate (CBR), Real Audio
- Transport protocols
  - Unicast: TCP (Reno, Vegas, etc.), UDP
  - Multicast: SRM (Scalable Reliable Multicast)
- Routing and queueing
  - Wired routing, Ad-hoc routing and Directed Diffusion
  - Queueing protocols: RED, drop-tail, etc.
- Physical media
  - Wired (point-to-point, LANs),
  - Wireless (multiple propagation models), Satellite communication

ns-2: Installation and Documentation

- Homepage: http://www.isi.edu/nsnam/ns/
  - Download ns-allinone
  - Includes Tcl, OTcl, TclCL, ns, nam, etc.
- Mailing list:
  - ns-users@isi.edu
- Documentation
  - Marc Gries tutorial
  - ns manual

The Network Simulator, ns-2

Using ns-2 for simulations

ns-2: Creating Event Scheduler

- Create scheduler
  - set ns [new Simulator]

- Schedule event
  - $ns at <time> <event>
  - <event>: any legitimate ns/tcl commands

- Start scheduler
  - $ns run

ns-2: Creating a Network

- Nodes
  - set n0 [$ns node]
  - set n1 [$ns node]

- Links & Queuing
  - $ns duplex-link $n0 $n1 <bandwidth> <delay> <queue_type>
  - <queue_type>: DropTail, RED, CBQ, FQ, SFQ, DRR, ...

ns-2: Computing Routes

- Unicast
  - $ns rtproto <type>
  - <type>: Static, Session, DV, cost, multi-path
- Multicast
  - $ns multicast
    - right after [new Simulator]
  - $ns mrtproto <type>
  - <type>: CtrMcast, DM, ST, BST

ns-2: Traffic

- Simple two layers: transport and application

- Transport protocols:
  - TCP, UDP, etc.

- Applications: (agents)
  - ftp, telnet, etc.

ns-2: Creating Connections (UDP)

- Source and sink
  - set usrc [new Agent/UDP]
  - set udst [new Agent/NULL]

- Connect them to nodes ...
  - $ns attach-agent $n0 $usrc
  - $ns attach-agent $n1 $udst

- ... then each other
  - $ns connect $usrc $udst

ns-2: Creating Connections (TCP)

- Source and sink
  - set tsrc [new Agent/TCP]
  - set tdst [new Agent/TCPSink]

- Connect them to nodes …
  - $ns attach-agent $n0 $tsrc
  - $ns attach-agent $n1 $tdst

- … then each other
  - $ns connect $tsrc $tdst

ns-2: Creating Traffic: On Top of TCP

- FTP
  - set ftp [new Application/FTP]
  - $ftp attach-agent $tsrc
  - $ns at <time> "$ftp start“

- Telnet set
  - telnet [new Application/Telnet]
  - $telnet attach-agent $tsrc

ns-2: Creating Traffic: On Top of UDP

- CBR
  - set src [new Application/Traffic/CBR]

- Exponential or Pareto on-off
  - set src [new Application/Traffic/Exponential]
  - set src [new Application/Traffic/Pareto]

ns-2: Creating Traffic: Trace Driven

- Trace driven
  - set tfile [new Tracefile]
  - $tfile filename <file>
  - set src [new Application/Traffic/Trace]
  - $src attach-tracefile $tfile

- <file>:
  - Binary format
  - inter-packet time (msec) and packet size (byte)

ns-2: End-to-End Argument: File Transfer

- Even if network guaranteed reliable delivery
  - Need to provide end-to-end checks
  - e.g., network card may malfunction

- If network is highly unreliable
  - Adding some level of reliability helps performance, not correctness
  - Don’t try to achieve perfect reliability!

OMNeT++

OMNeT++

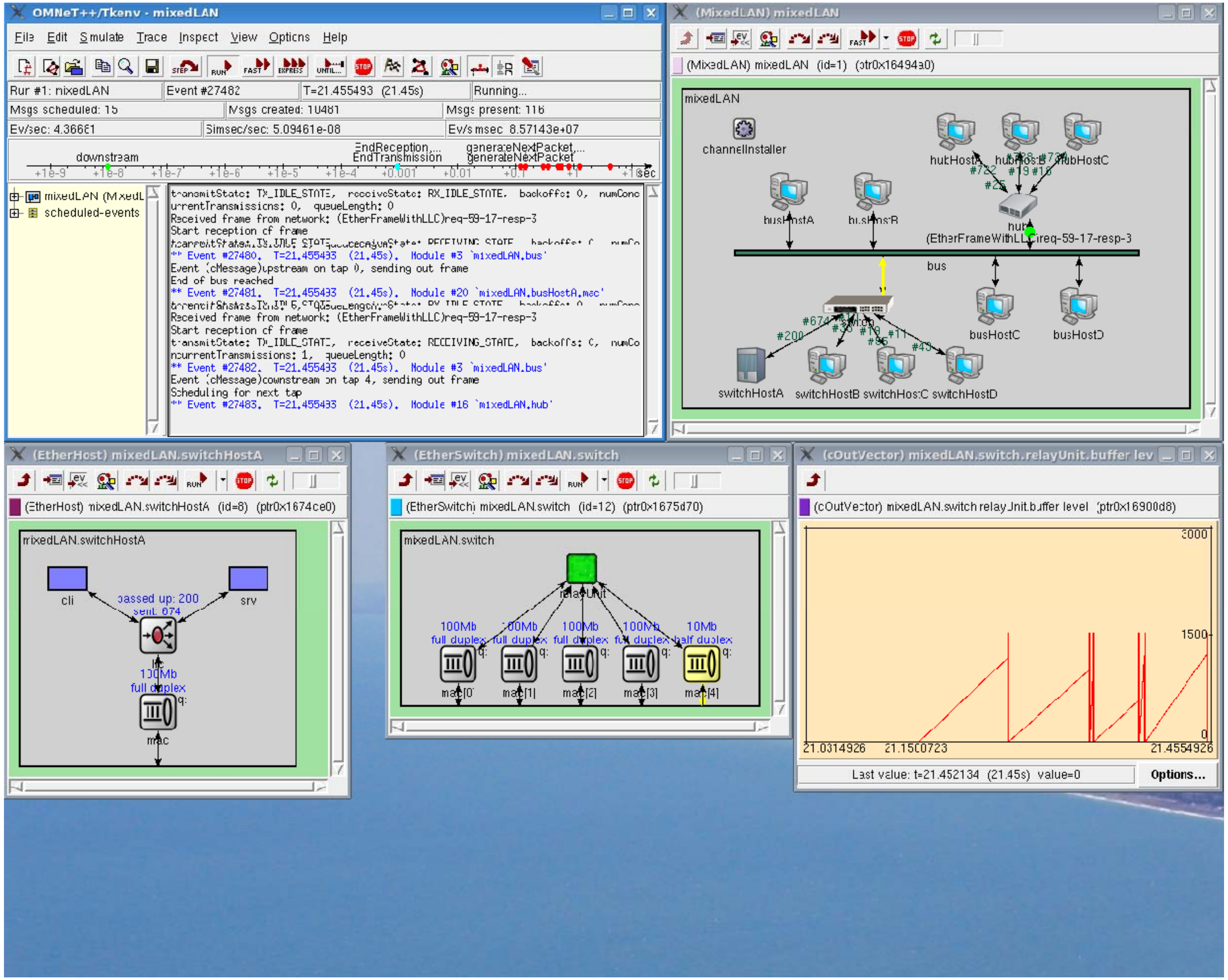
- Objective Modular Network Testbed in C++ (OMNeT++)
  - General-purpose tool for discrete event simulations
  - Object-oriented design

- Literature
  - OMNeT++ Community Site
    http://www.omnetpp.org
  - User Manual
    http://www.omnetpp.org/doc/manual/usman.html

OMNeT++
Goals

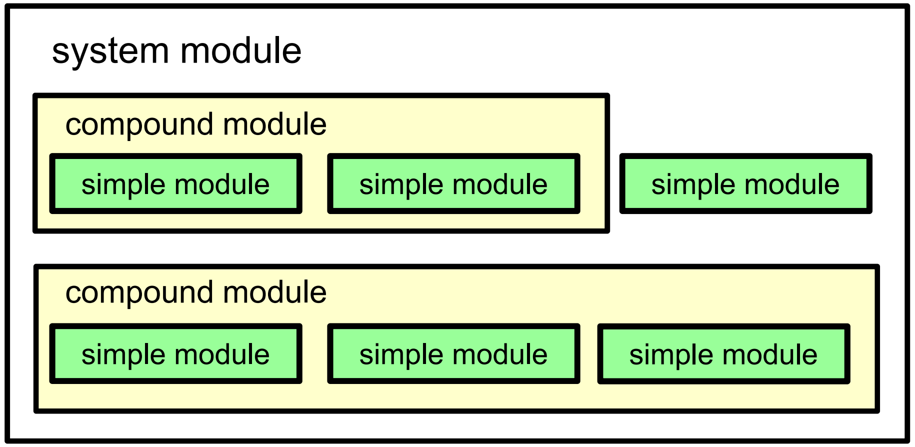
- The simulator can be used for:
  - traffic modeling of telecommunication networks
  - protocol modeling
  - modeling queueing networks
  - modeling multiprocessors and other distributed hardware systems
  - validating hardware architectures
  - evaluating performance aspects of complex software systems
  - ... modeling any other system where the discrete event approach is suitable.

OMNeT++ Screenshot



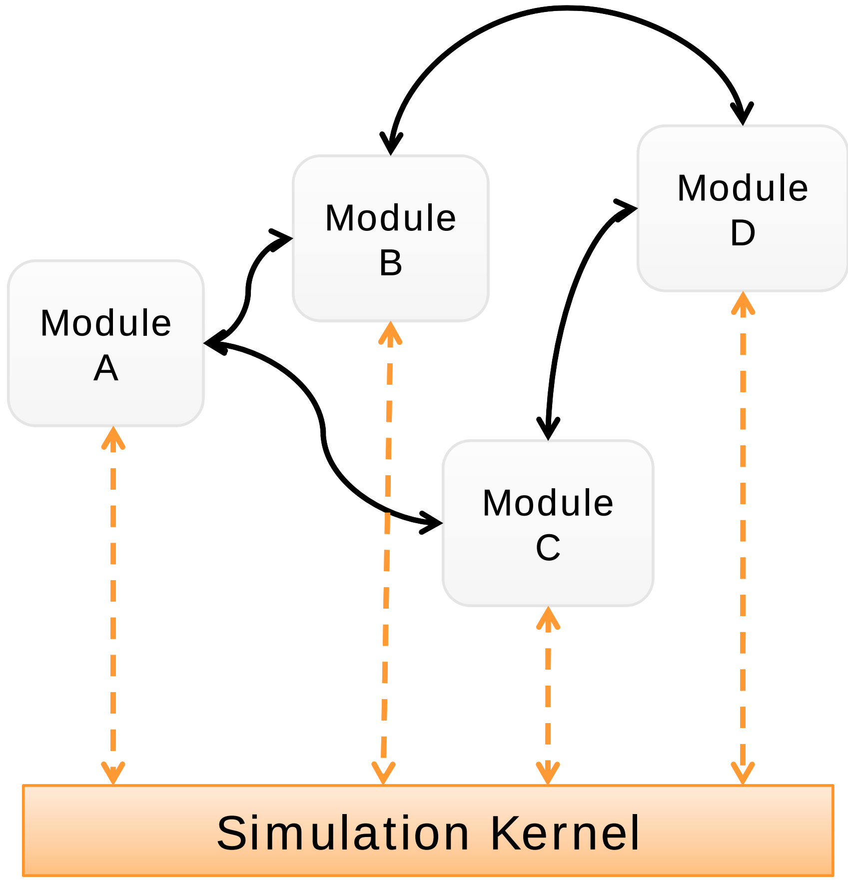
OMNeT++
Modules

- An OMNeT++ model consists of hierarchically nested modules
- Simple Modules
  - Lowest level of the module hierarchy
  - Simple modules contain the algorithms in the model
  - The user implements the simple modules in C++
    - Using the OMNeT++ simulation class library
- Compound Modules
  - Module contains submodules, which can also contain submodules themselves
  - Connects internal simple and compound modules
- The top level module is the system module



OMNeT++
Modules

- Relationship of modules
  - Modules communicate by passing messages to each another
  - Implement application-specific functionality
  - Connected by connections
  - Communication by exchanging messages via connections
  - Implemented as C++ objects
    - By using simulation library and general C++ stuff ;-)
  - Topology of module connections are specified in the NED language



OMNeT++ Parts of Simulation Programs

- NED-Files
  - OMNeT++ specific description language
- Modules
  - C++ Objects
    - Set of `blabla.cc` and `blabla.h` file
  - Describes behavior of components
- File: `omnetpp.ini`
  - Containing general settings for the execution of the simulation

OMNeT++

Network Description Language (NED)

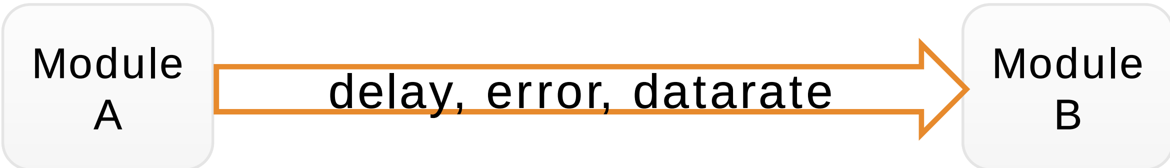
NED

- Network Description language (NED)
  - The topology of a model is specified using the NED language
  - Files containing network descriptions generally have a `.ned` suffix

- Elements of NED
  - Channel definitions
  - Simple module definitions
  - Compound module definitions
  - Connections
  - Network definitions

NED
Channels

- Specifies a connection type of given characteristics
- Channel name can be used later in the NED description
  - To create connections with these parameters
- Parameters
  - delay
    - Propagation delay in (simulated) seconds
  - error(rate)
    - Probability that a bit is incorrectly transmitted
  - datarate
    - Channel bandwidth in bits per second [bps]



NED
Channels – Example

- Syntax

```
channel ChannelName
 //...
endchannel
```

- Example

```
channel LeasedLine
    delay 0.0018     // sec
    error 1e-8
    datarate 128000  // bit per sec
endchannel
```

NED
Simple Module

- Simple modules are defined in NED file
  - Simple modules are the basic building blocks for other (compound) modules.

- Syntax

```
simple SimpleModuleName
 parameters:
    //...
 gates:
    //...
endsimple
```

NED
Simple Module

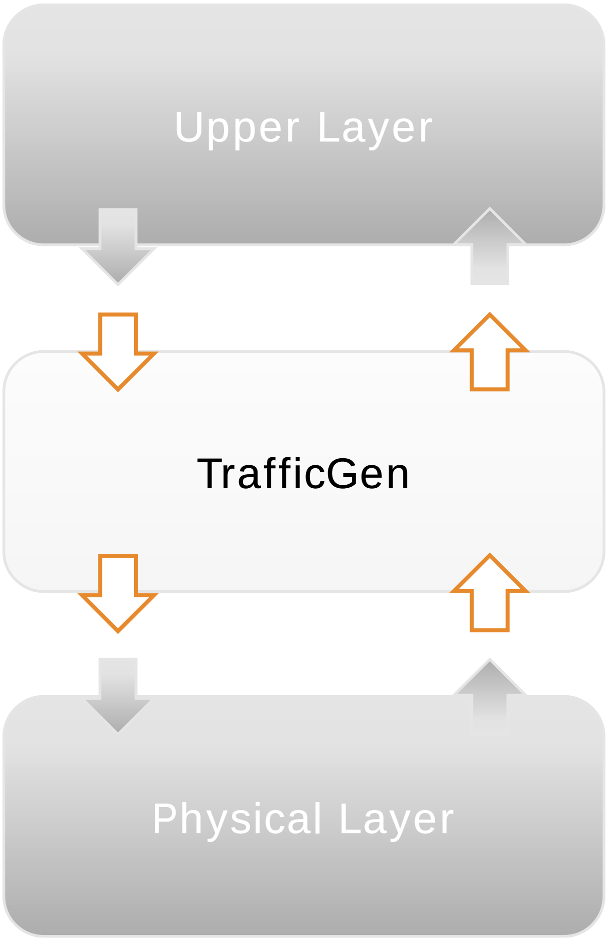
- Parameters
  - Values that can be set from a compound module or outside the simulation program, e.g., in configuration files
  - Parameters can be accessed from C++ code using **`cModule`**’s method: **`par(“name”)`**

- Gates
  - Gates are the connection points of modules.
  - OMNeT++ supports simplex (one-directional) connections
    - There are input and output gates.
  - Messages are sent through output gates and received through input gates.

NED
Simple Module – Example

- Traffic generator as simple module

```
simple TrafficGen
  parameters:
          interArrivalTime,
          numOfMessages     : const,
          address           : string;
  gates:
          in:  from_upper_layer,
               from_physical_layer;
          out: to_upper_layer,
               to_physical_layer;
endsimple
```



NED
Simple Module: Gates

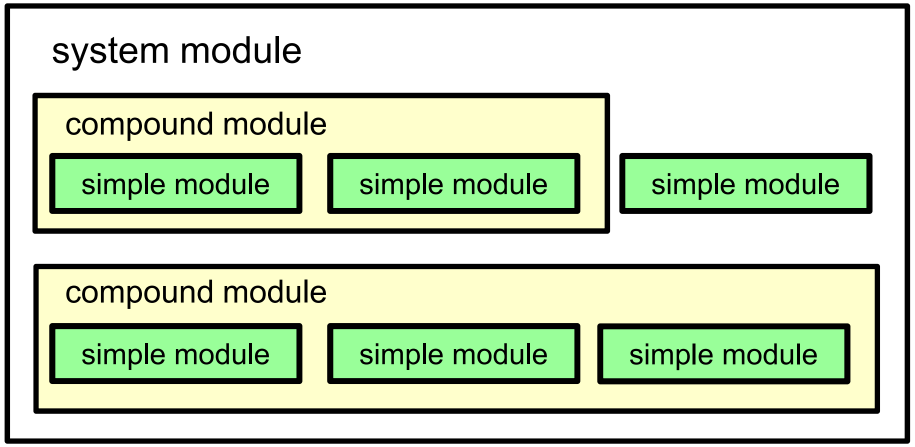
- Gate vectors are supported
  - A gate vector contains a number of single gates
- Example

```
simple RoutingModule
  parameters: // ...
  gates:
     in: input[];
     out: output[];
endsimple
```

- The sizes of gate vectors are given later
  - When the module is used as a building block of a compound module type
  - Every instance of the module can have gate vectors of different sizes

NED
Simple and Compound Module

- Compound Modules
  - Module contains submodules, which can also contain submodules themselves.
  - Any module type (simple or compound module) can be used as a submodule.
  - Like simple modules, compound modules can also have gates and parameters, and they can be used wherever simple modules can be used.
  - Connects internal simple and compound modules
- The top level module is the system module



NED
Compound Module

- Composed of one or more submodules
- Any module type can be used as a submodule
  - Simple or compound module
- Compound modules can also have gates and parameters
  - Like simple modules
- To the outside: behave like any other modules
  - Must offer gates
- To the inside: composing modules must be able to communicate somehow
  - Their gates must be connected

NED
Compound Module: Syntax

- Syntax

```
module CompoundModul
  parameters: …
  gates: …
  submodules: …
  connections:
endmodule
```

- Parameters and gates for compound modules are declared and work in the same way as with simple modules

NED
Compound Module: Example

- Compound module with parameter

```
module Router
  parameters:
         packetsPerSecond : numeric,
         bufferSize : numeric,
         numOfPorts : const;
  gates:
    in: inputPort[];
    out: outputPort[];
  submodules:  //...
  connections: //...
endmodule
```

NED
Compound Module: Submodules

- Defined in the "submodules:" section of a compound module declaration
- Identified by names
- Instances of a module type, either simple or compound
- Assign values to their parameters
- Specify the size of the gate vectors

- Syntax

```
module CompoundModule
  submodules:
      submodule1: ModuleType1
        parameters: //...
        gatesizes:  //...

      submodule2: ModuleType2
        parameters: //...
        gatesizes:  //...
endmodule
```

NED
Compound Module: Submodules

- It is possible to create an array of submodules (a module vector).

- Example

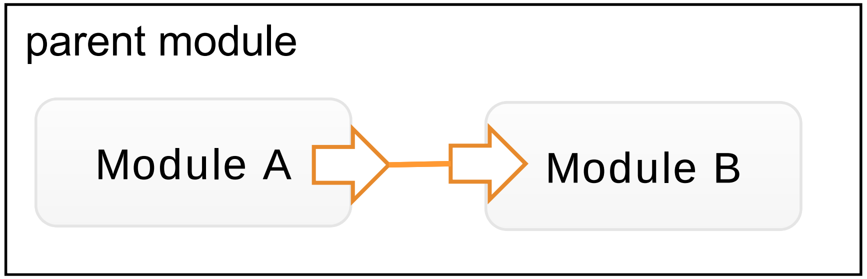
```
module CompoundModule
    parameters:
      size: const;
    submodules:
      submod1: Node[3] //...
      submod2: Node[size] //...
      submod3: Node[2*size+1] //...
endmodule
```

NED
Connections

- In compound module definition
- Specifies how the gates of the compound module and its immediate sub-modules are connected
- Only one-to-one connections are supported
- A connection
  - May have attributes (delay, bit error rate or data rate)
  - Or use a named channel

- Example

```
module CompoundModule
  parameters:    //...
  gates:         //...
  submodules:    //...
  connections:
    node1.output --> node2.input;
    node1.input <-- node2.output;
    sender.outGate --> rec.inGate;
    sender.inGate <-- Fiber <--
   rec.outGate;
    //...
endmodule
```



NED
Network Definition

- Module declarations (compound and simple module declarations) just define module types.
- Network definition to get a simulation model
- Syntax is similar to that of a submodule declaration
- Only module types without gates can be used in network definitions
- Assign values to submodule parameters

```
network wirelessLAN: WirelessLAN
 parameters:
    numUsers=10,
    httpTraffic=true,
    ftpTraffic=true,
    distanceFromHub=truncnormal(100,60);
endnetwork
```

OMNeT++

Implementation of Modules

C++ Classes

- cMessage
- cSimpleModule

C++ Classes: cMessage

- OMNeT++ uses messages to represent events
- Event represented by an instance of cMessage class
  - Or one of its subclasses
- Messages are sent from one module to another
  - This means that the place where the “event will occur” is the message's destination module
- Events like “timeout expired” are implemented by the module sending a message to itself

- Future Event Set (FES)
  - Events are inserted into the FES
  - Events are processed in strict timestamp order

C++ Classes: cMessage

- The message class in OMNeT++
- Represents events, messages, packets or other entities in a simulation
- Creating a message
  - `cMessage *msg = new cMessage();`
  - `cMessage *msg = new cMessage("MessageName");`
- Some methods
  - `msg->setKind(kind);`
  - `msg->setLength(length);`
  - `msg->setByteLength(lengthInBytes);`
  - `msg->setPriority(priority);`
  - `msg->setBitError(err);`
  - `msg->setTimestamp();`
  - `msg->setTimestamp(simtime);`

C++ Classes: cSimpleModule

- Simple modules of name `MyModule` implemented by a C++ class of name `MyModule`
  - Subclassing the `cSimpleModule` class

- Call the macro `Define_Module(MyModule)`after the definition of a C++ class
  - This macro couples the class to the NED module type

- Compound modules do not have a corresponding C++ class at all

C++ Classes: cSimpleModule

- Member functions
  - `void initialize()`
  - `void activity()`
  - `void handleMessage(cMessage *msg)`
  - `void finish()`

- `initialize()`
  - OMNeT++ calls the `initialize()` functions of all modules at start time.

- `finish()`
  - Called when the simulation terminates successfully, e.g., for recording of statistics collected during simulation run.

C++ Classes: cSimpleModule

- `handleMessage()` and `activity()` functions
  - Called during event processing.
  - User implements the model behavior in these functions.
  - `handleMessage()` and `activity()` implement different event processing strategies:
  - For each simple module, the user has to redefine **exactly one** of these functions.
- `handleMessage()`
  - Called by the simulation kernel when the module receives a message
- `activity()`
  - Coroutine-based solution which implements the process interaction approach

C++ Classes: cSimpleModule: Example

```cpp
// file: HelloModule.cc
#include <omnetpp.h>

class HelloModule : public cSimpleModule
{
  protected:
    virtual void initialize();
    virtual void handleMessage(cMessage *msg);
};

// register module class with OMNeT++
Define_Module(HelloModule);

void HelloModule::initialize()
{
    ev << "Hello World!\n";
}

void HelloModule::handleMessage(cMessage *msg)
{
    delete msg; // just discard everything we receive
}
```

C++ Classes: cSimpleModule

- Member function for sending messages
  - `send()` family of functions
    - to send messages to other modules
  - `scheduleAt()`
    - to schedule an event (the module “sends a message to itself”)
  - `cancelEvent()`
    - to delete an event scheduled with `scheduleAt()`

C++ Classes: cSimpleModule: Sending messages

- Message objects can be sent through an output gate
- Using one of the following functions
  - `send(cMessage *msg, const char *gateName, int index=0);`
    - gateName is the name of the gate in NED file
  - `send(cMessage *msg, int gateId);`
  - `send(cMessage *msg, cGate *gate);`
- Example
  - `send(msg, "outGate");`
  - `send(msg, "outGates", i); // send via outGates[i]`

C++ Classes: cSimpleModule: Self-messages

- Implement timers, or schedule events that occur at some point in the future
- The message would be delivered to the simple module at a later point of time
  - Through `handleMessage()`
  - Module can call `isSelfMessage()` to determine if it is a self-message

- Scheduling an event
  - `scheduleAt(absoluteTime, msg);`
  - `scheduleAt(simtime()+delta, msg);`

OMNeT++

An Example

Example

- The following example shows a useful simple module implementation.
- It demonstrates several of the discussed concepts:
  - constructor, initialize, and destructor conventions
  - using messages for timers
  - accessing module parameters
  - recording statistics at the end of the simulation
  - documenting the programmer's assumptions using ASSERT()

Example

```
// file: FFGenerator.h
#include <omnetpp.h>

/**
 * Generates messages or jobs; see NED file for more info.
 */
class FFGenerator : public cSimpleModule {
  private:
    cMessage *sendMessageEvent;
    long numSent;

  public:
    FFGenerator();
    virtual ~FFGenerator();

  protected:
    virtual void initialize();
    virtual void handleMessage(cMessage *msg);
    virtual void finish();
};
```

Example

```
// file: FFGenerator.cc
#include "FFGenerator.cc"

// Register module class with OMNeT++
Define_Module(FFGenerator);

FFGenerator::FFGenerator()
{
    sendMessageEvent = NULL;
}

void FFGenerator::initialize()
{
    numSent = 0;
    sendMessageEvent = new cMessage("sendMessageEvent");
    scheduleAt(0.0, sendMessageEvent);
}
```

Example

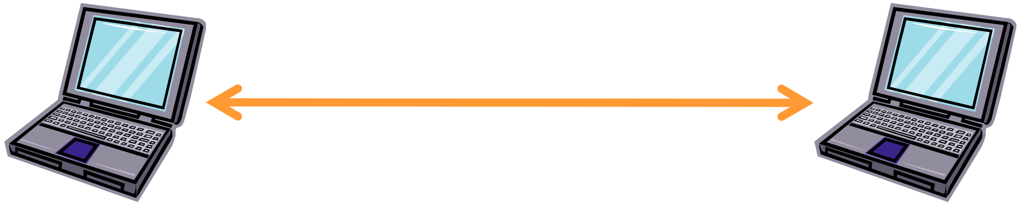
```
void FFGenerator::handleMessage(cMessage *msg) {
    ASSERT(msg==sendMessageEvent);
    cMessage *m = new cMessage("packet");
    m->setLength(par("msgLength"));
    send(m, "out");
    numSent++;

    double deltaT = (double)par("sendIaTime");
    scheduleAt(simTime()+deltaT, sendMessageEvent);
}

void FFGenerator::finish(){
    recordScalar("packets sent", numSent);
}

FFGenerator::~FFGenerator(){
    cancelAndDelete(sendMessageEvent);
}
```

Example

```
// file: FFGenerator.ned
simple FFGenerator
    parameters:
        sendIaTime: numeric;
    gates:
        out: out;
endsimple
```

Example

- Direct communication of two nodes

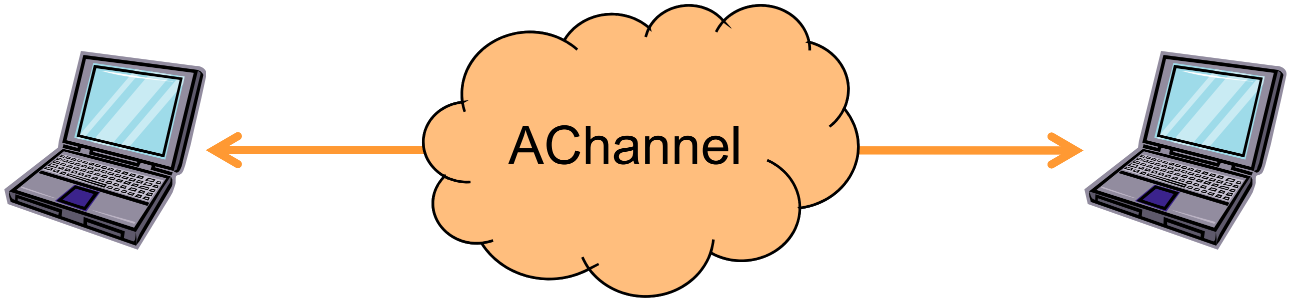


```
simple Node
    gates:
        in: inPort;
        out: outPort;
endsimple
```

```
module Network
    submodules:
        nodeA: Node;
        nodeB: Node;
    connections:
        nodeA.outPort --> nodeB.inPort;
        nodeA.inPort <-- nodeB.outPort;
endmodule
```

Example

- Communication over a channel




```
channel AChannel
    delay 0.0015
    error 0.000001
    datarate 1000000
endsimple
```

```
module Network
    submodules:
        nodeA: Node;
        nodeB: Node;
    connections:
        nodeA.outPort --> AChannel --> nodeB.inPort;
        nodeA.inPort <-- Achannel <-- nodeB.outPort;
endmodule
```

OMNeT++

Building Simulation Programs

Running the Simulation

- Linux
  - `opp_makemake -f  (generate Makefiles)`
  - `make depend`
  - `make`
  - `./X`
- Windows (Console)
  - `opp_nmakemake`
  - `nmake -f Makefile.vc`

Summary

- Discussed some network simulation tools

- ns-2 is one of the most used network simulators
  - Contains many protocol and application components
  - Widely accepted

- OMNeT++ is a modern and modular simulation system
  - Cleanly structured object-oriented design
  - Provides access to both event- and process-based programming style
  - A lot of support functionality