INET Framework User's Guide

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This manual is written for users who are interested in assembling simulations using the components provided by the INET Framework. (In contrast, if you are interested in modifying INET's components or plan to extend INET with new protocols or other components using C++, we recommend the INET Developer's Guide.)

CHAPTER

ONE

INTRODUCTION

1.1 What is INET Framework

INET Framework is an open-source model library for the OMNeT++ simulation environment. It provides protocols, agents and other models for researchers and students working with communication networks. INET is especially useful when designing and validating new protocols, or exploring new or exotic scenarios.

INET supports a wide class of communication networks, including wired, wireless, mobile, ad hoc and sensor networks. It contains models for the Internet stack (TCP, UDP, IPv4, IPv6, OSPF, BGP, etc.), link layer protocols (Ethernet, PPP, IEEE 802.11, various sensor MAC protocols, etc), refined support for the wireless physical layer, MANET routing protocols, DiffServ, MPLS with LDP and RSVP-TE signalling, several application models, and many other protocols and components. It also provides support for node mobility, advanced visualization, network emulation and more.

Several other simulation frameworks take INET as a base, and extend it into specific directions, such as vehicular networks, overlay/peer-to-peer networks, or LTE.

1.2 Designed for Experimentation

INET is built around the concept of modules that communicate by message passing. Agents and network protocols are represented by components, which can be freely combined to form hosts, routers, switches, and other networking devices. New components can be programmed by the user, and existing components have been written so that they are easy to understand and modify.

INET benefits from the infrastructure provided by OMNeT++. Beyond making use of the services provided by the OMNeT++ simulation kernel and library (component model, parameterization, result recording, etc.), this also means that models may be developed, assembled, parameterized, run, and their results evaluted from the comfort of the OMNeT++ Simulation IDE, or from the command line.

INET Framework is maintained by the OMNeT++ team for the community, utilizing patches and new models contributed by members of the community.

1.3 Scope of this Manual

This manual is written for users who are interested in assembling simulations using the components provided by the INET Framework. (In contrast, if you are interested in modifing INET's components or plan to extend INET with new protocols or other components using C++, we recommend the *INET Developers Guide*.)

This manual does not attempt to be a reference for INET. It concentrates on conveying the big picture, and does not attempt to cover all components, or try to document the parameters, gates, statistics or precise operation of individual components. For such information, users should refer to the *INET Reference*, a web-based cross-referenced documentation generated from NED and MSG files.

A working knowledge of OMNeT++ is assumed.

CHAPTER

TWO

USING THE INET FRAMEWORK

2.1 Installation

There are several ways to install the INET Framework:

- Let the OMNeT++ IDE download and install it for you. This is the easiest way. Just accept the offer to install INET in the dialog that comes up when you first start the IDE, or choose *Help → Install Simulation Models* any time later.
- From INET Framework web site, *http://inet.omnetpp.org*. The IDE always installs the last stable version compatible with your version of OMNeT++. If you need some other version, they are available for download from the web site. Installation instructions are also provided there.
- From GitHub. If you have experience with *git*, clone the INET Framework project (`inet-framework/inet`), check out the revision of your choice, and follow the INSTALL file in the project root.

2.2 Installing INET Extensions

If you plan to make use of INET extensions (e.g. Veins or SimuLTE), follow the installation instructions provided with them.

In the absence of specific instructions, the following procedure usually works:

- First, check if the project root contains a file named `.project`.
- If it does, then the project can be imported into the IDE (use *File → Import → General → Existing Project* into workspace). Make sure that the project is recognized as an OMNeT++ project (the *Project Properties* dialog contains a page titled *OMNeT++*), and it lists the INET project as dependency (check the *Project References* page in the *Project Properties* dialog).
- If there is no `.project` file, you can create an empty OMNeT++ project using the *New OMNeT++ Project* wizard in *File → New*, add the INET project as dependency using the *Project References* page in the *Project Properties* dialog, and copy the source files into the project.

2.3 Getting Familiar with INET

The INET Framework builds upon OMNeT++, and uses the same concept: modules that communicate by message passing. Hosts, routers, switches and other network devices are represented by OMNeT++ compound modules. These compound modules are assembled from simple modules that represent protocols, applications, and other functional units. A network is again an OMNeT++ compound module that contains host, router and other modules.

Modules are organized into a directory structure that roughly follows OSI layers:

- `src/inet/applications/` – traffic generators and application models
- `src/inet/transportlayer/` – transport layer protocols

- `src/inet/networklayer/` – network layer protocols and accessories
- `src/inet/linklayer/` – link layer protocols and accessories
- `src/inet/physicallayer/` – physical layer models
- `src/inet/routing/` – routing protocols (internet and ad hoc)
- `src/inet/mobility/` – mobility models
- `src/inet/power/` – energy consumption modeling
- `src/inet/environment/` – model of the physical environment
- `src/inet/node/` – preassembled network node models
- `src/inet/visualizer/` – visualization components (2D and 3D)
- `src/inet/common/` – miscellaneous utility components

The OMNeT++ NED language uses hierarchical packages names. Packages correspond to directories under `src/`, so e.g. the `src/inet/transportlayer/tcp` directory corresponds to the `inet.transportlayer.tcp` NED package.

For modularity, the INET Framework has about 80 *project features* (parts of the codebase that can be disabled as a unit) defined. Not all project features are enabled in the default setup after installation. You can review the list of available project features in the *Project → Project Features...* dialog in the IDE. If you want to know more about project features, refer to the *OMNeT++ User Guide*.

CHAPTER

THREE

NETWORKS

3.1 Overview

INET heavily builds upon the modular architecture of OMNeT++. It provides numerous domain specific and highly parameterizable components which can be combined in many ways. The primary means of building large custom network simulations in INET is the composition of existing models with custom models, starting from small components and gradually forming ever larger ones up until the composition of the network. Users are not required to have programming experience to create simulations unless they also want to implement their own protocols, for example.

Assembling an INET simulation starts with defining a module representing the network. Networks are compound modules which contain network nodes, automatic network configurators, and sometimes additionally transmission medium, physical environment, various visualizer, and other infrastructure related modules. Networks also contain connections between network nodes representing cables. Large hierarchical networks may be further organized into compound modules to directly express the hierarchy.

There are no predefined networks in INET, because it is very easy to create one, and because of the vast possibilities. However, the OMNeT++ IDE provides several topology generator wizards for advanced scenarios.

As INET is an OMNeT++-based framework, users mainly use NED to describe the model topology, and ini files to provide configuration.[1]

3.2 Built-in Network Nodes and Other Top-Level Modules

INET provides several pre-assembled network nodes with carefully selected components. They support customization via parameters and parametric submodule types, but they are not meant to be universal. Sometimes it may be necessary to create special network node models for particular simulation scenarios. In any case, the following list gives a taste of the built-in network nodes.

- StandardHost contains the most common Internet protocols: UDP, TCP, IPv4, IPv6, Ethernet, IEEE 802.11. It also supports an optional mobility model, optional energy models, and any number of applications which are entirely configurable from INI files.
- EtherSwitch models an Ethernet switch containing a relay unit and one MAC unit per port.
- Router provides the most common routing protocols: OSPF, BGP, RIP, PIM.
- AccessPoint models a Wifi access point with multiple IEEE 802.11 network interfaces and multiple Ethernet ports.
- WirelessHost provides a network node with one (default) IEEE 802.11 network interface in infrastructure mode, suitable for using with an AccessPoint.
- AdhocHost is a WirelessHost with the network interface configured in ad-hoc mode and forwarding enabled.

[1] Some components require additional configuration to be provided as separate files, e.g. in XML.

Network nodes communicate at the network level by exchanging OMNeT++ messages which are the abstract representations of physical signals on the transmission medium. Signals are either sent through OMNeT++ connections in the wired case, or sent directly to the gate of the receiving network node in the wireless case. Signals encapsulate INET-specific packets that represent the transmitted digital data. Packets are further divided into chunks that provide alternative representations for smaller pieces of data (e.g. protocol headers, application data).

Additionally, there are components that occur on network level, but they are not models of physical network nodes. They are necessary to model other aspects. Some of them are:

- A *radio medium* module such as Ieee80211RadioMedium, ApskScalarRadioMedium and UnitDiskRadioMedium (there are a few of them) are a required component of wireless networks.
- PhysicalEnvironment models the effect of the physical environment (i.e. obstacles) on radio signal propagation. It is an optional component.
- *Configurators* such as Ipv4NetworkConfigurator, L2NetworkConfigurator and NextHopNetworkConfigurator configure various aspects of the network. For example, Ipv4NetworkConfigurator assigns IP addresses to hosts and routers, and sets up static routing. It is used when modeling dynamic IP address assignment (e.g. via DHCP) or dynamic routing is not of importance. L2NetworkConfigurator allows one to configure 802.1 LANs and provide STP/RSTP-related parameters such as link cost, port priority and the "is-edge" flag.
- ScenarioManager allows scripted scenarios, such as timed failure and recovery of network nodes.
- *Group coordinators* are needed for the operation of some group mobility mdels. For example, MoBanCoordinator is the coordinator module for the MoBAN mobility model.
- *Visualizers* like PacketDropOsgVisualizer provide graphical rendering of some aspect of the simulation either in 2D (canvas) or 3D (using OSG or osgEarth). The usual choice is IntegratedVisualizer which bundles together an instance of each specific visualizer type in a compound module.

3.3 Typical Networks

3.3.1 Wired Networks

Wired network connections, for example Ethernet cables, are represented with standard OMNeT++ connections using the DatarateChannel NED type. The channel's `datarate` and `delay` parameters must be provided for all wired connections. The number of wired interfaces in a host (or router) usually does not need to be manually configured, because it can be automatically inferred from the actual number of links to neighbor nodes.

The following example shows how straightforward it is to create a model for a simple wired network. This network contains a server connected to a router using PPP, which in turn is connected to a switch using Ethernet. The network also contains a parameterizable number of clients, all connected to the switch forming a star topology. The utilized network nodes are all predefined modules in INET. To avoid the manual configuration of IP addresses and routing tables, an automatic network configurator is also included.

```
network WiredNetworkExample
{
    parameters:
        int numClients; // number of clients in the network
    submodules:
        configurator: Ipv4NetworkConfigurator; // network autoconfiguration
        server: StandardHost; // predefined standard host
        router: Router; // predefined router
        switch: EtherSwitch; // predefined ethernet switch
        client[numClients]: StandardHost;
    connections: // network level connections
        router.pppg++ <--> { datarate = 1GBps; } <--> server.pppg++; // PPP
        switch.ethg++ <--> Eth1G <--> router.ethg++; // bidirectional ethernet
        for i=0..numClients-1 {
            client[i].ethg++ <--> Eth1G <--> switch.ethg++; // ethernet
```

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```
        }
}
```

In order to run a simulation using the above network, an OMNeT++ INI file must be created. The INI file selects the network, sets its number of clients parameter, and configures a simple TCP application for each client. The server is configured to have a TCP application which echos back all data received from the clients individually.

```
network = WiredNetworkExample
*.numClients = 10 # number of clients in network
*.client[*].numApps = 1 # number of applications on clients
*.client[*].app[0].typename = "TcpSessionApp" # client application type
*.client[*].app[0].connectAddress = "server" # destination address
*.client[*].app[0].connectPort = 1000 # destination port
*.client[*].app[0].sendBytes = 1MB # amount of data to send
*.server.numApps = 1 # number of applications on server
*.server.app[0].typename = "TcpEchoApp" # server application type
*.server.app[0].localPort = 1000 # TCP server listen port
```

When the above simulation is run, each client application connects to the server using a TCP socket. Then each one of them sends 1MB of data, which in turn is echoed back by the server, and the simulation concludes. The default statistics are written to the `results` folder of the simulation for later analysis.

3.3.2 Wireless Networks

Wireless network connections are not modeled with OMNeT++ connections due the dynamically changing nature of connectivity. For wireless networks, an additional module, one that represents the transmission medium, is required to maintain connectivity information.

```
network WirelessNetworkExample
    submodules:
        configurator: Ipv4NetworkConfigurator;
        radioMedium: Ieee80211ScalarRadioMedium;
        host1: WirelessHost { @display("p=200,100"); }
        host2: WirelessHost { @display("p=500,100"); }
        accessPoint: AccessPoint { @display("p=374,200"); }
}
```

In the above network, positions in the display strings provide positions for the transmission medium during the computation of signal propagation and path loss.

In addition, `host1` is configured to periodically send UDP packets to `host2` over the AP.

```
network = WirelessNetworkExample
*.host1.numApps = 1
*.host1.app[0].typename = "UdpBasicApp"
*.host1.app[0].destAddresses = "host2"
*.host1.app[0].destPort = 1000
*.host1.app[0].messageLength = 100Byte
*.host1.app[0].sendInterval = 100ms
*.host2.numApps = 1
*.host2.app[0].typename = "UdpSink"
*.host2.app[0].localPort = 1000
**.arp.typename = "GlobalArp"
**.netmaskRoutes = ""
```

3.3.3 Mobile Ad hoc Networks

```
network MobileAdhocNetworkExample
{
    parameters:
        int numHosts; // number of nodes in the network
    submodules:
        configurator: Ipv4NetworkConfigurator; // network autoconfiguration
        radioMedium: Ieee80211ScalarRadioMedium; // 802.11 physical medium
        host[numHosts]: AdhocHost; // ad-hoc wifi nodes
}
```

```
network = MobileAdhocNetworkExample
*.numHosts = 10 # number of hosts in the MANET
*.host[*].mobility.typename = "MassMobility" # stochastic mobility model
*.host[*].mobility.initFromDisplayString = false # ignore display string
*.host[*].mobility.changeInterval = truncnormal(2s, 0.5s) # between turns
*.host[*].mobility.angleDelta = normal(0deg, 30deg) # random turn
*.host[*].mobility.speed = truncnormal(20mps, 8mps) # random speed
*.host[*].numApps = 1 # number of applications on hosts
*.host[*].app[0].typename = "PingApp" # application type for all hosts
*.host[*].app[0].destAddr = "host[0]" # ping destination
*.host[*].app[0].startTime = uniform(1s,5s) # to avoid synchronization
*.host[*].app[0].printPing = true # print usual ping results to stdout
```

3.4 Frequent Tasks (How To. . .)

This section contains quick and somewhat superficial advice to many practical tasks.

3.4.1 Automatic Wired Interfaces

In many wired network simulations, the number of wired interfaces need not be manually configured, because it can be automatically inferred from the actual number of connections between network nodes.

```
router1.ethg++ <--> Eth1G <--> router2.ethg++; // automatic interfaces
```

3.4.2 Multiple Wireless Interfaces

All built-in wireless network nodes support multiple wireless interfaces, but only one is enabled by default.

```
*.host[*].numWlanInterfaces = 2 # number of wireless network interfaces
*.host[*].wlan[0].agent.defaultSsid = "alpha" # connects to alpha network
*.host[*].wlan[1].agent.defaultSsid = "bravo" # connects to bravo network
```

3.4.3 Specifying Addresses

Nearly all application layer modules, but several other components as well, have parameters that specify network addresses. They typically accept addresses given with any of the following syntax variations:

- literal IPv4 address: `"186.54.66.2"`
- literal IPv6 address: `"3011:7cd6:750b:5fd6:aba3:c231:e9f9:6a43"`
- module name: `"server"`, `"subnet.server[3]"`
- interface of a host or router: `"server/eth0"`, `"subnet.server[3]/eth0"`

- IPv4 or IPv6 address of a host or router: `"server(ipv4)"`, `"subnet.server[3](ipv6)"`
- IPv4 or IPv6 address of an interface of a host or router: `"server/eth0(ipv4)"`, `"subnet.server[3]/eth0(ipv6)"`

3.4.4 Node Failure and Recovery

3.4.5 Enabling Dual IP Stack

All built-in network nodes support dual Internet protocol stacks, that is both IPv4 and IPv6 are available. They are also supported by transport layer protocols, link layer protocols, and most applications. Only IPv4 is enabled by default, so in order to use IPv6, it must be enabled first, and an application supporting IPv6 (e.g., PingApp must be used). The following example shows how to configure two ping applications in a single node where one is using an IPv4 and the other is using an IPv6 destination address.

```
*.host[*].hasIpv4 = true # enable IPv4 protocol
*.host[*].hasIpv6 = true # enable IPv6 protocol
*.host[*].numApps = 2 # number of applications on hosts
*.host[*].app[*].typename = "PingApp" # type for both applications
*.host[*].app[0].destAddr = "host[0](ipv4)" # uses IPv4 detination address
*.host[*].app[1].destAddr = "host[0](ipv6)" # uses IPv6 detination address
```

3.4.6 Enabling Packet Forwarding

In general, network nodes don't forward packets by default, only Router and the like do. Nevertheless, it's possible to enable packet forwarding as simply as flipping a switch.

```
*.host[*].forwarding = true
```

CHAPTER

FOUR

NETWORK NODES

4.1 Overview

Hosts, routers, switches, access points, mobile phones, and other network nodes are represented in INET with compound modules. The previous chapter has introduced a few node types like StandardHost, Router, and showed how to put together networks from them. In this chapter, we look at the internals of such node models, in order to provide a deeper understanding of their customization possibilities and to give some guidance on how custom nodes models can be assembled.

4.2 Ingredients

Node models are assembled from other modules which represent applications, communication protocols, network interfaces, routing tables, mobility models, energy models, and other functionality. These modules fall into the following broad categories:

- *Applications* often model the user behavior as well as the application program (e.g., browser), and the application layer protocol (e.g., HTTP). Applications typically use transport layer protocols (e.g., TCP and/or UDP), but they may also directly use lower layer protocols (e.g., IP or Ethernet) via sockets.
- *Routing protocols* are provided as separate modules: OSPF, BGP, or AODV for MANET routing. These modules use TCP, UDP, and IPv4, and manipulate routes in the Ipv4RoutingTable module.
- *Transport layer protocols* are connected to applications and network layer protocols. They are most often represented by simple modules, currently TCP, UDP, and SCTP are supported. TCP has several implementations: Tcp is the OMNeT++ native implementation; TcpLwip module wraps the lwIP TCP stack; and TcpNsc module wraps the Network Simulation Cradle library.
- *Network layer protocols* are connected to transport layer protocols and network interfaces. They are usually modeled as compound modules: Ipv4NetworkLayer for IPv4, and Ipv6NetworkLayer for IPv6. The Ipv4NetworkLayer module contains several protocol modules: Ipv4, Arp, Icmp and Icmpv6.
- *Network interfaces* are represented by compound modules which are connected to the network layer protocols and other network interfaces in the wired case. They are often modeled as compound modules containing separate modules for queues, classifiers, MAC, and PHY protocols.
- *Link layer protocols* are usually simple modules sitting in network interface modules. Some protocols, for example IEEE 802.11 MAC, are modeled as a compound module themselves due to the complexity of the protocol.
- *Physical layer protocols* are compound modules also being part of network interface modules.
- *Interface table* maintains the set of network interfaces (e.g. `eth0`, `wlan0`) in the network node. Interfaces are registered dynamically during initialization of network interfaces.
- *Routing tables* maintain the list of routes for the corresponding network protocol (e.g., Ipv4RoutingTable for Ipv4). Routes are added by automatic network configurators or routing protocols. Network protocols use the routing tables to find out the best matching route for datagrams.

- *Mobility modules* are responsible for moving around the network node in the simulated scene. The mobility model is mandatory for wireless simulations even if the network node is stationary. The mobility module stores the location of the network node which is needed to compute wireless propagation and path loss. Different mobility models are provided as different modules. Network nodes define their mobility submodule with a parametric type, so the mobility model can be changed in the configuration.
- *Energy modules* model energy storage mechanisms, energy consumption of devices and software processes, energy generation of devices, and energy management processes which shutdown and startup network nodes.
- *Status* (NodeStatus) keeps track of the status of the network node (up, down, etc.)
- *Other modules* with particular functionality such as PcapRecorder are also available.

4.3 Node Architecture

Within network nodes, OMNeT++ connections are used to represent communication opportunities between protocols. Packets and messages sent on these connections represent software or hardware activity.

Although protocols may also be connected to each other directly, in most cases they are connected via *dispatcher modules*. Dispatchers (MessageDispatcher) are small, low-overhead modules that allow protocol components to be connected in one-to-many and many-to-many fashion, and ensure that messages and packets sent from one component end up being delivered to the correct component. Dispatchers need no manual configuration, as they use discovery and peek into packets.

In there pre-assembled node models, dispatchers allow arbitrary protocol components to talk directly to each other, i.e. not only to ones in neighboring layers.

4.4 Customizing Nodes

The built-in network nodes are written to be as versatile and customizable as possible. This is achieved in several ways:

4.4.1 Submodule and Gate Vectors

One way is the use of gate vectors and submodule vectors. The sizes of vectors may come from parameters or derived by the number of external connections to the network node. For example, a host may have an arbitrary number of wireless interfaces, and it will automatically have as many Ethernet interfaces as the number of Ethernet devices connected to it.

For example, wireless interfaces for hosts are defined like this:

```
wlan[numWlanInterfaces]: <snip> // wlan interfaces in StandardHost etc al.
```

Where `numWlanInterfaces` is a module parameter that defaults to either 0 or 1 (this is different for e.g. StandardHost and WirelessHost.) To configure a host to have two interfaces, add the following line to the ini file:

```
**.hostA.numWlanInterfaces = 2
```

4.4.2 Conditional Submodules

Submodules that are not vectors are often conditional. For example, the TCP protocol module in hosts is conditional on the `hasTcp` parameter. Thus, to disable TCP support in a host (it is enabled by default), use the following ini file line:

```
**.hostA.hasTcp = false
```

4.4.3 Parametric Types

Another often used way of customization is parametric types, that is, the type of a submodule (or a channel) may be specified as a string parameter. Almost all submodules in the built-in node types have parametric types. For example, the TCP protocol module is defined like this:

```
tcp: <default("Tcp")> like ITcp if hasTcp;
```

The `typename` parameter of the tcp submodule defaults to the default implementation, Tcp. To use another implementation instead, add the following line to the ini file:

```
**.host*.tcp.typename = "TcpLwip"  # use lwIP's TCP implementation
```

Submodule vectors with parametric types are defined without the use of a module parameter to allow elements have different types. An example is how applications are defined in hosts:

```
app[numApps]: <> like IApp;  // applications in StandardHost et al.
```

And applications can be added in the following way:

```
**.hostA.numApps = 2
**.hostA.apps[0].typename = "UdpBasicApp"
**.hostA.apps[1].typename = "PingApp"
```

4.4.4 Inheritance

Inheritance can be use to derive new, specialized node types from existing ones. A derived NED type may add new parameters, gates, submodules or connections, and may set inherited unassigned parameters to specific values.

For example, WirelessHost is derived from StandardHost in the following way:

```
module WirelessHost extends StandardHost
{
    @display("i=device/wifilaptop");
    numWlanInterfaces = default(1);
}
```

4.5 Custom Network Nodes

Despite the many pre-assembled network nodes and the several available customization options, sometimes it is just easier to build a network node from scratch. The following example shows how easy it is to build a simple network node.

This network node already contains a configurable application and several standard protocols. It also demonstrates how to use the packet dispatching mechanism which is required to connect multiple protocols in a many-to-many relationship.

```
module NetworkNodeExample
{
    parameters:
    gates:
        inout ethg; // ethernet interface connector
        input radioIn; // incoming radio frames from physical medium
    submodules:
        app: <> like IApp; // configurable application
        tcp: Tcp; // standard TCP protocol
        ip: Ipv4; // standard IP protocol
        md: MessageDispatcher; // connects multiple interfaces to IP
        wlan: Ieee80211Interface; // standard wifi interface
        eth: EthernetInterface; // standard ethernet interface
        interfaceTable: InterfaceTable;
    connections: // network node internal connections
        app.socketOut --> tcp.appIn; // application sends data stream
        app.socketIn <-- tcp.appOut; // application receives data stream
        tcp.ipOut --> ip.transportIn; // TCP sends segments
        tcp.ipIn <-- ip.transportOut; // TCP receives segments
        ip.queueOut --> md.in++; // IP sends datagrams
        ip.queueIn <-- md.out++; // IP receives datagrams
        md.out++ --> wlan.upperLayerIn;
        md.in++ <-- wlan.upperLayerOut;
        md.out++ --> eth.upperLayerIn;
        md.in++ <-- eth.upperLayerOut;
        eth.phys <--> ethg; // Ethernet sends frames to cable
        radioIn --> wlan.radioIn; // IEEE 802.11 sends frames to medium
}
```

CHAPTER

FIVE

NETWORK INTERFACES

5.1 Overview

In INET simulations, network interface modules are the primary means of communication between network nodes. They represent the required combination of software and hardware elements from an operating system point-of-view.

Network interfaces are implemented with OMNeT++ compound modules that conform to the INetworkInterface module interface. Network interfaces can be further categorized as wired and wireless; they conform to the IWiredInterface and IWirelessInterface NED types, respectively, which are subtypes of INetworkInterface.

5.2 Built-in Network Interfaces

INET provides pre-assembled network interfaces for several standard protocols, protocol tunneling, hardware emulation, etc. The following list gives the most commonly used network interfaces.

- EthernetInterface represents an Ethernet interface
- PppInterface is for wired links using PPP
- Ieee80211Interface represents a Wifi (IEEE 802.11) interface
- Ieee802154NarrowbandInterface and Ieee802154UwbIrInterface represent a IEEE 802.15.4 interface
- BMacInterface, LMacInterface, XMacInterface provide low-power wireless sensor MAC protocols along with a simple hypothetical PHY protocol
- TunInterface is a tunneling interface that can be directly used by applications
- LoopbackInterface provides local loopback within the network node
- ExtLowerEthernetInterface represents a real-world interface, suitable for hardware-in-the-loop simulations

5.3 Anatomy of Network Interfaces

Network interfaces in the INET Framework are OMNeT++ compound modules that contain many more components than just the corresponding layer 2 protocol implementation. Most of these components are optional, i.e. absent by default, and can be added via configuration.

Typical ingredients are:

- *Layer 2 protocol implementation*. For some interfaces such as PppInterface this is a single module; for others like Ethernet and Wifi it consists of separate modules for MAC, LLC, and possibly other subcomponents.
- *PHY model*. Some interfaces also contain separate module(s) that implement the physical layer. For example, Ieee80211Interface contains a radio module.

- *Output queue*. This module allows one to experiment with different queueing policies and implement QoS, RED, etc.
- *Traffic conditioners* allow traffic shaping and policing elements to be added to the interface, for example to implement a Diffserv router.
- *Hooks* allow extra modules to be inserted in the incoming and outgoing paths of packets.

5.3.1 Internal vs External Output Queue

Network interfaces usually have a queue module defined with a parametric type like this:

```
queue: <default("DropTailQueue")> like IPacketQueue;
```

When the `typename` parameter of the queue submodule is unspecified (this is the default), the queue module is a DropTailQueue. Conceptually, the queue is of inifinite size, but for better diagnostics one can often specify a hard limit for the queue length in a module parameter – if this is exceeded, the simulation stops with an error.

When the `typename` parameter of the queue module is not empty, it must name a NED type that implements the IPacketQueue interface. The queue module model allows modeling a finite buffer, or implement various queueing policies for QoS and/or RED.

The most frequently used module type for the queue module is DropTailQueue, a finite-size FIFO that drops overflowing packets). Other queue types that implement queueing policies can be created by assembling compound modules from queueing model and DiffServ components (see chapter *Differentiated Services*). An example of such compound modules is DiffservQueue.

An example ini file fragment that installs a priority queue on PPP interfaces:

```
**.ppp[*].ppp.queue.typename = "PriorityQueue"
**.ppp[*].ppp.queue.packetCapacity = 10
**.ppp[*].ppp.queue.numQueues = 2
**.ppp[*].ppp.queue.classifier.typename = "WrrClassifier"
**.ppp[*].ppp.queue.classifier.weights = "1 1"
```

5.3.2 Traffic Conditioners

Many network interfaces contain optional traffic conditioner submodules defined with parametric types, like this:

```
ingressTC: <default("")> like ITrafficConditioner if typename != "";
egressTC: <default("")> like ITrafficConditioner if typename != "";
```

Traffic conditioners allow one to implement the policing and shaping actions of a Diffserv router. They are added to the input or output packets paths in the network interface. (On the output path they are added before the queue module.)

Traffic conditioners must implement the ITrafficConditioner module interface. Traffic conditioners can be assembled from DiffServ components (see chapter *Differentiated Services*). There is no preassembled traffic conditioner in INET, but you can find some in the example simulations.

An example configuration with fictituous types:

```
**.ppp[*].ingressTC.typename = "CustomIngressTC"
**.ppp[*].egressTC.typename = "CustomEgressTC"
```

5.3.3 Hooks

Several network interfaces allow extra modules to be inserted in the incoming and outgoing paths of packets at the top of the netwok interface. Hooks are added as a submodule vector with parametric type, like this:

```
outputHook[numOutputHooks]: <default("Nop")> like IHook if numOutputHooks>0;
inputHook[numInputHooks]: <default("Nop")> like IHook if numInputHooks>0;
```

This allows any number of hook modules to be added. The hook modules are chained in their numeric order.

Modules inserted as hooks may act as probes (for measuring or recording traffic) or as means of modifying or perturbing the packet flow for experimentation. Module types implementing the IHook NED interface include ThruputMeter, Delayer, OrdinalBasedDropper, and OrdinalBasedDuplicator.

The following ini file fragment inserts two hook modules into the output paths of PPP interfaces, a delayer and a throughput meter:

```
**.ppp[*].numOutputHooks = 2
**.ppp[*].outputHook[0].typename = "Delayer"
**.ppp[*].outputHook[1].typename = "ThruputMeter"
**.ppp[*].outputHook[0].delay = 3ms
```

5.4 The Interface Table

Network nodes normally contain an InterfaceTable module. The interface table is a sort of registry of all the network interfaces in the host. It does not send or receive messages, other modules access it via C++ function calls. Contents of the interface table can also be inspected e.g. in Qtenv.

Network interfaces register themselves in the interface table at the beginning of the simulation. Registration is usually the task of the MAC (or equivalent) module.

5.5 Wired Network Interfaces

Wired interfaces have a pair of special purpose OMNeT++ gates which represent the capability of having an external physical connection to another network node (e.g. Ethernet port). In order to make wired communication work, these gates must be connected with special connections which represent the physical cable between the physical ports. The connections must use special OMNeT++ channels (e.g. DatarateChannel) which determine datarate and delay parameters.

Wired network interfaces are compound modules that implement the IWiredInterface interface. INET has the following wired network interfaces.

5.5.1 PPP

Network interfaces for point-to-point links (PppInterface) are described in chapter *Point-to-Point Links*. They are typically used in routers.

5.5.2 Ethernet

Ethernet interfaces (EthernetInterface), alongside with models of Ethernet devices such as switches and hubs, are described in chapter *The Ethernet Model*.

5.6 Wireless Network Interfaces

Wireless interfaces use direct sending[1] for communication instead of links, so their compound modules do not have output gates at the physical layer, only an input gate dedicated to receiving. Another difference from the wired case is that wireless interfaces require (and collaborate with) a *transmission medium* module at the network level. The medium module represents the shared transmission medium (electromagnetic field or acoustic medium), is responsible for modeling physical effects like signal attenuation, and maintains connectivity information. Also, while wired interfaces can do without explicit modeling of the physical layer, a PHY module is an indispensable part of a wireless interface.

Wireless network interfaces are compound modules that implement the IWirelessInterface interface. In the following sections we give an overview of the wireless interfaces available in INET.

5.6.1 Generic Wireless Interface

The WirelessInterface compound module is a generic implementation of IWirelessInterface. In this network interface, the types of the MAC protocol and the PHY layer (the radio) are parameters:

```
mac: <> like IMacProtocol;
radio: <> like IRadio if typename != "";
```

There are specialized versions of WirelessInterface where the MAC and the radio modules are fixed to a particular value. One example is BMacInterface, which contains a BMac and an ApskRadio.

5.6.2 IEEE 802.11

IEEE 802.11 or Wifi network interfaces (Ieee80211Interface), alongside with models of devices acting as access points (AP), are covered in chapter *The 802.11 Model*.

5.6.3 IEEE 802.15.4

Ieee802154NarrowbandInterface is covered in a separate chapter, see *The 802.15.4 Model*.

5.6.4 Wireless Sensor Networks

MAC protocols for wireless sensor networks (WSNs) and the corresponding network interfaces are covered in chapter *MAC Protocols for Wireless Sensor Networks*.

[1] OMNeT++ `sendDirect()` calls

5.6.5 CSMA/CA

CsmaCaMac implements an imaginary CSMA/CA-based MAC protocol with optional acknowledgements and a retry mechanism. With the appropriate settings, it can approximate basic 802.11b ad-hoc mode operation.

CsmaCaMac provides a lot of room for experimentation: acknowledgements can be turned on/off, and operation parameters like inter-frame gap sizes, backoff behaviour (slot time, minimum and maximum number of slots), maximum retry count, header and ACK frame sizes, bit rate, etc. can be configured via NED parameters.

CsmaCaInterface interface is a WirelessInterface with the MAC type set to CsmaCaMac.

5.6.6 Acking MAC

Not every simulation requires a detailed simulation of the lower layers. AckingWirelessInterface is a highly abstracted wireless interface that offers simplicity for scenarios where Layer 1 and 2 effects can be completely ignored, for example testing the basic functionality of a wireless ad-hoc routing protocol.

AckingWirelessInterface is a WirelessInterface parameterized to contain a unit disk radio (UnitDiskRadio) and a trivial MAC protocol (AckingMac).

The most important parameter UnitDiskRadio accepts is the transmission range. When a radio transmits a frame, all other radios within transmission range are able to receive the frame correctly, and radios that are out of range will not be affected at all. Interference modeling (collisions) is optional, and it is recommended to turn it off with AckingMac.

AckingMac implements a trivial MAC protocol that has packet encapsulation and decapsulation, but no real medium access procedure. Frames are simply transmitted on the wireless channel as soon as the transmitter becomes idle. There is no carrier sense, collision avoidance, or collison detection. AckingMac also provides an optional out-of-band acknowledgement mechanism (using C++ function calls, not actual wirelessly sent frames), which is turned on by default. There is no retransmission: if the acknowledgement does not arrive after the first transmission, the MAC gives up and counts the packet as failed transmission.

5.6.7 Shortcut

ShortcutMac implements error-free "teleportation" of packets to the peer MAC entity, with some delay computed from a transmission duration and a propagation delay. The physical layer is completely bypassed. The corresponding network interface type, ShortcutInterface, does not even have a radio model.

ShortcutInterface is useful for modeling wireless networks where full connectivity is assumed, and Layer 1 and Layer 2 effects can be completely ignored.

5.7 Special-Purpose Network Interfaces

5.7.1 Tunnelling

TunInterface is a virtual network interface that can be used for creating tunnels, but it is more powerful than that. It lets an application-layer module capture packets sent to the TUN interface and do whatever it pleases with it (including sending it to a peer entity in an UDP or plain IPv4 packet.)

To set up a tunnel, add an instance of TunnelApp to the node, and specify the protocol (IPv4 or UDP) and the remote endpoint of the tunnel (address and port) in parameters.

5.7.2 Local Loopback

LoopbackInterface provides local loopback within the network node.

5.7.3 External Interfaces

ExtLowerEthernetInterface represents a real-world interface, suitable for hardware-in-the-loop simulations. External interfaces are explained in chapter *Network Emulation*.

5.8 Custom Network Interfaces

It's also possible to build custom network interfaces, the following example shows how to build a custom wireless interface.

```
module WirelessInterfaceExample
{
    gates:
        input upperLayerIn; // packets from network layer in the same host
        output upperLayerOut; // packets to network layer in the same host
        input radioIn; // incoming packets from other hosts in the network
    submodules:
        mac: AckingMac; // simple MAC supporting ACKs
        radio: ApskScalarRadio; // simple radio supporting many modulations
    connections: // network interface internal connections
        mac.upperLayerOut --> upperLayerOut;
        mac.upperLayerIn <-- upperLayerIn;
        radio.upperLayerOut --> mac.lowerLayerIn;
        radio.upperLayerIn <-- mac.lowerLayerOut;
        radioIn --> radio.radioIn;
}
```

The above network interface contains very simple hypothetical MAC and PHY protocols. The MAC protocol only provides acknowledgment without other services (e.g., carrier sense, collision avoidance, collision detection), the PHY protocol uses one of the predefined APSK modulations for the whole signal (preamble, header, and data) without other services (e.g., scrambling, interleaving, forward error correction).

CHAPTER

SIX

APPLICATIONS

6.1 Overview

This chapter describes application models and traffic generators. All applications implement the IApp module interface to ease configuration. For example, StandardHost contains an application submodule vector that can be filled in with specific applications from the INI file.

INET applications fall into two categories. In the first category, applications implement very specific behaviors, and generate corresponding traffic patterns based on their specific parameters. These applications are implemented as simple modules.

In the second category, applications are more generic. They separate traffic generation from the usage of the protocol, Udp or Tcp for example. These applications are implemented as compound modules. They contain separate configurable traffic source, traffic sink, and protocol input/output submodules. This approach allows building complex traffic patterns by composing queueing model elements.

6.2 TCP applications

This sections describes the applications using the TCP protocol. These applications use GenericAppMsg objects to represent the data sent between the client and server. The client message contains the expected reply length, the processing delay, and a flag indicating that the connection should be closed after sending the reply. This way intelligence (behaviour specific to the modelled application, e.g. HTTP, SMB, database protocol) needs only to be present in the client, and the server model can be kept simple and dumb.

6.2.1 TcpBasicClientApp

Client for a generic request-response style protocol over TCP. May be used as a rough model of HTTP or FTP users.

The model communicates with the server in sessions. During a session, the client opens a single TCP connection to the server, sends several requests (always waiting for the complete reply to arrive before sending a new request), and closes the connection.

The server app should be TcpGenericServerApp; the model sends GenericAppMsg messages.

Example settings:

FTP:

```
numRequestsPerSession = exponential(3)
requestLength = truncnormal(20,5)
replyLength = exponential(1000000)
```

HTTP:

```
numRequestsPerSession = 1 # HTTP 1.0
numRequestsPerSession = exponential(5)  # HTTP 1.1, with keepalive
requestLength = truncnormal(350,20)
replyLength = exponential(2000)
```

Note that since most web pages contain images and may contain frames, applets etc, possibly from various servers, and browsers usually download these items in parallel to the main HTML document, this module cannot serve as a realistic web client.

Also, with HTTP 1.0 it is the server that closes the connection after sending the response, while in this model it is the client.

6.2.2 TcpSinkApp

Accepts any number of incoming TCP connections, and discards whatever arrives on them.

6.2.3 TcpGenericServerApp

Generic server application for modelling TCP-based request-reply style protocols or applications.

The module accepts any number of incoming TCP connections, and expects to receive messages of class GenericAppMsg on them. A message should contain how large the reply should be (number of bytes). TcpGenericServerApp will just change the length of the received message accordingly, and send back the same message object. The reply can be delayed by a constant time (`replyDelay` parameter).

6.2.4 TcpEchoApp

The TcpEchoApp application accepts any number of incoming TCP connections, and sends back the data that arrives on them, The byte counts are multiplied by `echoFactor` before echoing. The reply can also be delayed by a constant time (`echoDelay` parameter).

6.2.5 TcpSessionApp

Single-connection TCP application: it opens a connection, sends the given number of bytes, and closes. Sending may be one-off, or may be controlled by a "script" which is a series of (time, number of bytes) pairs. May act either as client or as server. Compatible with both IPv4 and IPv6.

Opening the connection

Depending on the type of opening the connection (active/passive), the application may be either a client or a server. In passive mode, the application will listen on the given local local port, and wait for an incoming connection. In active mode, the application will bind to given local local address and local port, and connect to the given address and port. It is possible to use an ephemeral port as local port.

Even when in server mode (passive open), the application will only serve one incoming connection. Further connect attempts will be refused by TCP (it will send RST) for lack of LISTENing connections.

The time of opening the connection is in the `tOpen` parameter.

Sending data

Regardless of the type of OPEN, the application can be made to send data. One way of specifying sending is via the `tSend`, `sendBytes` parameters, the other way is `sendScript`. With the former, `sendBytes` bytes will be sent at `tSend`. When using `sendScript`, the format of the script is:

```
<time> <numBytes>; <time> <numBytes>;...
```

Closing the connection

The application will issue a TCP CLOSE at time `tClose`. If `tClose=-1`, no CLOSE will be issued.

6.2.6 TelnetApp

Models Telnet sessions with a specific user behaviour. The server app should be TcpGenericServerApp.

In this model the client repeats the following activity between `startTime` and `stopTime`:

1. Opens a telnet connection
2. Sends `numCommands` commands. The command is `commandLength` bytes long. The command is transmitted as entered by the user character by character, there is `keyPressDelay` time between the characters. The server echoes each character. When the last character of the command is sent (new line), the server responds with a `commandOutputLength` bytes long message. The user waits `thinkTime` interval between the commands.
3. Closes the connection and waits `idleInterval` seconds
4. If the connection is broken, it is noticed after `reconnectInterval` and the connection is reopened

Each parameter in the above description is "volatile", so you can use distributions to emulate random behaviour.

Note: This module emulates a very specific user behaviour, and as such, it should be viewed as an example rather than a generic Telnet model. If you want to model realistic Telnet traffic, you are encouraged to gather statistics from packet traces on a real network, and write your model accordingly.

6.2.7 TcpServerHostApp

This module hosts TCP-based server applications. It dynamically creates and launches a new "thread" object for each incoming connection.

Server threads can be implemented in C++. An example server thread class is `TcpGenericServerThread`.

6.2.8 Applications composing TCP traffic

The following TCP modules are provided to allow composing applications with more complex traffic without implementing new C++ modules:

- TcpClientApp: generic TCP client application with composable traffic source and traffic sink
- TcpServerApp: generic TCP server application with a TCP server listener to create TCP server connections
- TcpServerConnection: generic TCP server connection with composable traffic source and traffic sink
- TcpServerListener: generic TCP server listener for accepting/rejecting TCP connections and for creating TCP server connections
- TcpRequestResponseApp: generic request-response based TCP server application with configurable pre-composed traffic source and traffic sink

There are some applications which model the traffic of the telnet protocol:

- TelnetClientApp: telnet client application with configurable pre-composed telnet traffic source and traffic sink
- TelnetServerApp: telnet server application with pre-configured TCP server listener to create telnet server connections
- TelnetServerConnection: telnet server connection with configurable pre-composed telnet traffic source and traffic sink

6.3 UDP applications

The following UDP-based applications are implemented in INET:

- UdpBasicApp sends UDP packets to a given IP address at a given interval
- UdpBasicBurst sends UDP packets to the given IP address(es) in bursts, or acts as a packet sink.
- UdpEchoApp is similar to UdpBasicApp, but it sends back the packet after reception
- UdpSink consumes and prints packets received from the Udp module
- UdpVideoStreamClient,:ned:*UdpVideoStreamServer* simulates video streaming over UDP

The next sections describe these applications in details.

6.3.1 UdpBasicApp

The UdpBasicApp sends UDP packets to a the IP addresses given in the `destAddresses` parameter. The application sends a message to one of the targets in each `sendInterval` interval. The interval between message and the message length can be given as a random variable. Before the packet is sent, it is emitted in the signal.

The application simply prints the received UDP datagrams. The signal can be used to detect the received packets.

6.3.2 UdpSink

This module binds an UDP socket to a given local port, and prints the source and destination and the length of each received packet.

6.3.3 UdpEchoApp

Similar to UdpBasicApp, but it sends back the packet after reception. It accepts only packets with UdpHeader, i.e. packets that are generated by another UdpEchoApp.

When an echo response received, it emits an signal.

6.3.4 UdpVideoStreamClient

This module is a video streaming client. It send one "video streaming request" to the server at time `startTime` and receives stream from UdpVideoStreamServer.

The received packets are emitted by the signal.

6.3.5 UdpVideoStreamServer

This is the video stream server to be used with UdpVideoStreamClient.

The server will wait for incoming "video streaming requests". When a request arrives, it draws a random video stream size using the `videoSize` parameter, and starts streaming to the client. During streaming, it will send UDP packets of size `packetLen` at every `sendInterval`, until `videoSize` is reached. The parameters `packetLen` and `sendInterval` can be set to constant values to create CBR traffic, or to random values (e.g. `sendInterval=uniform(1e-6, 1.01e-6)`) to accomodate jitter.

The server can serve several clients, and several streams per client.

6.3.6 UdpBasicBurst

Sends UDP packets to the given IP address(es) in bursts, or acts as a packet sink. Compatible with both IPv4 and IPv6.

Addressing

The `destAddresses` parameter can contain zero, one or more destination addresses, separated by spaces. If there is no destination address given, the module will act as packet sink. If there are more than one addresses, one of them is randomly chosen, either for the whole simulation run, or for each burst, or for each packet, depending on the value of the `chooseDestAddrMode` parameter. The `destAddrRNG` parameter controls which (local) RNG is used for randomized address selection. The own addresses will be ignored.

An address may be given in the dotted decimal notation, or with the module name. (The `L3AddressResolver` class is used to resolve the address.) You can use the "Broadcast" string as address for sending broadcast messages.

INET also defines several NED functions that can be useful:

- `moduleListByPath("pattern",...)`:
  Returns a space-separated list of the modulenames. All modules whose full path matches one of the pattern parameters will be included. The patterns may contain wilcards in the same syntax as in ini files. Example:
- `moduleListByNedType("fully.qualified.ned.type",...)`:
  Returns a space-separated list of the modulenames with the given NED type(s). All modules whose NED type name occurs in the parameter list will be included. The NED type name is fully qualified. Example:

Examples:

```
**.app[0].destAddresses = moduleListByPath("**.host[*]", "**.fixhost[*]")
**.app[1].destAddresses = moduleListByNedType("inet.nodes.inet.StandardHost")
```

The peer can be UDPSink or another UDPBasicBurst.

Bursts

The first burst starts at `startTime`. Bursts start by immediately sending a packet; subsequent packets are sent at `sendInterval` intervals. The `sendInterval` parameter can be a random value, e.g. `exponential(10ms)`. A constant interval with jitter can be specified as `1s+uniform(-0.01s,0.01s)` or `uniform(0.99s,1.01s)`. The length of the burst is controlled by the `burstDuration` parameter. (Note that if `sendInterval` is greater than `burstDuration`, the burst will consist of one packet only.) The time between burst is the `sleepDuration` parameter; this can be zero (zero is not allowed for `sendInterval`.) The zero `burstDuration` is interpreted as infinity.

Operation as sink

When `destAddresses` parameter is empty, the module receives packets and makes statistics only.

6.3.7 Applications composing UDP traffic

The following UDP modules are provided to allow composing applications with more complex traffic without implementing new C++ modules:

- UdpApp: generic UDP application with composable traffic source and traffic sink
- UdpClientApp: generic UDP client application with composable traffic source and traffic sink
- UdpServerApp: generic UDP server application with a UDP session handler to create UDP server sessions
- UdpServerSession: generic UDP server session with composable traffic source and traffic sink
- UdpRequestResponseApp: generic request-response based UDP server application with configurable pre-composed traffic source and traffic sink

6.4 IPv4/IPv6 traffic generators

The applications described in this section use the services of the network layer only, they do not need transport layer protocols. They can be used with both IPv4 and IPv6.

IIpvxTrafficGenerator (prototype) sends IP or IPv6 datagrams to the given address at the given `sendInterval`. The `sendInterval` parameter can be a constant or a random value (e.g. `exponential(1)`). If the `destAddresses` parameter contains more than one address, one of them is randomly for each packet. An address may be given in the dotted decimal notation (or, for IPv6, in the usual notation with colons), or with the module name. (The `L3AddressResolver` class is used to resolve the address.) To disable the model, set `destAddresses` to "".

The IpvxTrafGen sends messages with length `packetLength`. The sent packet is emitted in the signal. The length of the sent packets can be recorded as scalars and vectors.

The IpvxTrafSink can be used as a receiver of the packets generated by the traffic generator. This module emits the packet in the signal and drops it. The `rcvdPkBytes` and `endToEndDelay` statistics are generated from this signal.

The IpvxTrafGen can also be the peer of the traffic generators; it handles the received packets exactly like IpvxTrafSink.

6.5 The PingApp application

The PingApp application generates ping requests and calculates the packet loss and round trip parameters of the replies.

Start/stop time, sendInterval etc. can be specified via parameters. An address may be given in the dotted decimal notation (or, for IPv6, in the usual notation with colons), or with the module name. (The `L3AddressResolver` class is used to resolve the address.) To disable send, specify empty destAddr.

Every ping request is sent out with a sequence number, and replies are expected to arrive in the same order. Whenever there's a jump in the in the received ping responses' sequence number (e.g. 1, 2, 3, 5), then the missing pings (number 4 in this example) is counted as lost. Then if it still arrives later (that is, a reply with a sequence number smaller than the largest one received so far) it will be counted as out-of-sequence arrival, and at the same time the number of losses is decremented. (It is assumed that the packet arrived was counted earlier as a loss, which is true if there are no duplicate packets.)

6.6 Ethernet applications

The `inet.applications.ethernet` package contains modules for a simple client-server application. The EtherAppClient is a simple traffic generator that peridically sends EtherAppReq messages whose length can be configured. destAddress, startTime,waitType, reqLength, respLength

The server component of the model (EtherAppServer) responds with a EtherAppResp message of the requested length. If the response does not fit into one ethernet frame, the client receives the data in multiple chunks.

Both applications have a `registerSAP` boolean parameter. This parameter should be set to `true` if the application is connected to the EtherLlc module which requires registration of the SAP before sending frames.

Both applications collects the following statistics: sentPkBytes, rcvdPkBytes, endToEndDelay.

The client and server application works with any model that accepts Ieee802Ctrl control info on the packets (e.g. the 802.11 model). The applications should be connected directly to the EtherLlc or an EthernetInterface NIC module.

The model also contains a host component that groups the applications and the LLC and MAC components together (EtherHost). This node does not contain higher layer protocols, it generates Ethernet traffic directly. By default it is configured to use half duplex MAC (CSMA/CD).

CHAPTER

SEVEN

TRANSPORT PROTOCOLS

7.1 Overview

In the OSI reference model, the protocols of the transport layer provide host-to-host communication services for applications. They provide services such as connection-oriented communication, reliability, flow control, and multiplexing.

INET currently provides support for the TCP, UDP, SCTP and RTP transport layer protocols. INET nodes like StandardHost contain optional and replaceable instances of these protocols, like this:

```
tcp: <default("Tcp")> like ITcp if hasTcp;
udp: <default("Udp")> like IUdp if hasUdp;
sctp: <default("Sctp")> like ISctp if hasSctp;
```

As RTP is more specialized that the other ones (multimedia streaming), INET provides a separate node type, RtpHost, for modeling RTP traffic.

7.2 TCP

7.2.1 Overview

TCP protocol is the most widely used protocol of the Internet. It provides reliable, ordered delivery of stream of bytes from one application on one computer to another application on another computer. The baseline TCP protocol is described in RFC793, but other tens of RFCs contains modifications and extensions to the TCP. As a result, TCP is a complex protocol and sometimes it is hard to see how the different requirements interact with each other.

INET contains three implementations of the TCP protocol:

- Tcp is the primary implementation, designed for readability, extensibility, and experimentation.
- TcpLwip is a wrapper around the lwIP (Lightweight IP) library, a widely used open source TCP/IP stack designed for embedded systems.
- TcpNsc wraps Network Simulation Cradle (NSC), a library that allows real world TCP/IP network stacks to be used inside a network simulator.

All three module types implement the ITcp interface and communicate with other layers through the same interface, so they can be interchanged and also mixed in the same network.

7.2.2 Tcp

The Tcp simple module is the main implementation of the TCP protocol in the INET framework.

Tcp implements the following:

- TCP state machine
- initial sequence number selection according to the system clock.
- window-based flow control
- Window Scale option
- Persistence timer
- Keepalive timer
- Transmission policies
- RTT measurement for retransmission timeout (RTO) computation
- Delayed ACK algorithm
- Nagle's algorithm
- Silly window avoidance
- Timestamp option
- Congestion control schemes: Tahoe, Reno, New Reno, Westwood, Vegas, etc.
- Slow Start and Congestion Avoidance
- Fast Retransmit and Fast Recovery
- Loss Recovery Using Limited Transmit
- Selective Acknowledgments (SACK)
- SACK based loss recovery

Several protocol features can be turned on/off with parameters like `delayedAcksEnabled`, `nagleEnabled`, `limitedTransmitEnabled`, `increasedIWEnabled`, `sackSupport`, `windowScalingSupport`, or `timestampSupport`.

The congestion control algorithm can be selected with the `tcpAlgorithmClass` parameter. For example, the following ini file fragment selects TCP Vegas:

```
**.tcp.tcpAlgorithmClass = "TcpVegas"
```

Values like `"TcpVegas"` name C++ classes. Indeed, Tcp can be extended with new congestion control schemes by implementing and registering them in C++.

7.2.3 TcpLwip

lwIP is a light-weight implementation of the TCP/IP protocol suite that was originally written by Adam Dunkels of the Swedish Institute of Computer Science. The current development homepage is http://savannah.nongnu.org/projects/lwip/.

The implementation targets embedded devices: it has very limited resource usage (it works "with tens of kilobytes of RAM and around 40 kilobytes of ROM"), and does not require an underlying OS.

The TcpLwip simple module is based on the 1.3.2 version of the lwIP sources.

Features:

- delayed ACK
- Nagle's algorithm

- round trip time estimation
- adaptive retransmission timeout
- SWS avoidance
- slow start threshold
- fast retransmit
- fast recovery
- persist timer
- keep-alive timer

Limitations

- only MSS and TS TCP options are supported. The TS option is turned off by default, but can be enabled by defining LWIP_TCP_TIMESTAMPS to 1 in `lwipopts.h`.
- `fork` must be `true` in the passive open command
- The status request command (TCP_C_STATUS) only reports the local and remote addresses/ports of the connection and the MSS, SND.NXT, SND.WND, SND.WL1, SND.WL2, RCV.NXT, RCV.WND variables.

7.2.4 TcpNsc

Network Simulation Cradle (NSC) is a tool that allow real-world TCP/IP network stacks to be used in simulated networks. The NSC project is created by Sam Jansen and available on http://research.wand.net.nz/software/nsc.php. NSC currently contains Linux, FreeBSD, OpenBSD and lwIP network stacks, although on 64-bit systems only Linux implementations can be built.

To use the TcpNsc module you should download the `nsc-0.5.2.tar.bz2` package and follow the instructions in the `<inet_root>/3rdparty/README` file to build it.

Warning: Before generating the INET module, check that the `opp_makemake` call in the make file (`<inet_root>/Makefile`) includes the `-DWITH_TCP_NSC` argument. Without this option the TcpNsc module is not built. If you build the INET library from the IDE, it is enough to enable the *TCP (NSC)* project feature.

Parameters

The module has the following parameters:

- `stackName`: the name of the TCP implementation to be used. Possible values are: `liblinux2.6.10.so`, `liblinux2.6.18.so`, `liblinux2.6.26.so`, `libopenbsd3.5.so`, `libfreebsd5.3.so` and `liblwip.so`. (On the 64 bit systems, the `liblinux2.6.26.so` and `liblinux2.6.16.so` are available only).
- `stackBufferSize`: the size of the receive and send buffer of one connection for selected TCP implementation. The NSC sets the `wmem_max`, `rmem_max`, `tcp_rmem`, `tcp_wmem` parameters to this value on linux TCP implementations. For details, you can see the NSC documentation.

Limitations

- Because the kernel code is not reentrant, NSC creates a record containing the global variables of the stack implementation. By default there is room for 50 instance in this table, so you can not create more then 50 instance of TcpNsc. You can increase the `NUM_STACKS` constant in `num_stacks.h` and recompile NSC to overcome this limitation.
- The TcpNsc module does not supprt TCP_TRANSFER_OBJECT data transfer mode.
- The MTU of the network stack fixed to 1500, therefore MSS is 1460.
- TCP_C_STATUS command reports only local/remote addresses/ports and current window of the connection.

7.3 UDP

The UDP protocol is a very simple datagram transport protocol, which basically makes the services of the network layer available to the applications. It performs packet multiplexing and demultiplexing to ports and some basic error detection only.

The Udp simple module implements the UDP protocol. There is a module interface (IUdp) that defines the gates of the Udp component. In the StandardHost node, the UDP component can be any module implementing that interface.

7.4 SCTP

The Sctp module implements the Stream Control Transmission Protocol (SCTP). Like TCP, SCTP provides reliable ordered data delivery over an ureliable network. The most prominent feature of SCTP is the capability of transmitting multiple streams of data at the same time between two end points that have established a connection.

7.5 RTP

The Real-time Transport Protocol (RTP) is a transport layer protocol for delivering audio and video over IP networks. RTP is used extensively in communication and entertainment systems that involve streaming media, such as telephony, video teleconference applications including WebRTC, television services and web-based push-to-talk features.

The RTP Control Protocol (RTCP) is a sister protocol of the Real-time Transport Protocol (RTP). RTCP provides out-of-band statistics and control information for an RTP session.

INET provides the following modules:

- Rtp implements the RTP protocol
- Rtcp implements the RTCP protocol

CHAPTER

EIGHT

THE IPV4 PROTOCOL FAMILY

8.1 Overview

The IP protocol is the workhorse protocol of the TCP/IP protocol suite. All UDP, TCP, ICMP packets are encapsulated into IP datagrams and transported by the IP layer. While higher layer protocols transfer data among two communication end-point, the IP layer provides an hop-by-hop, unreliable and connectionless delivery service. IP does not maintain any state information about the individual datagrams, each datagram handled independently.

The nodes that are connected to the Internet can be either a host or a router. The hosts can send and recieve IP datagrams, and their operating system implements the full TCP/IP stack including the transport layer. On the other hand, routers have more than one interface cards and perform packet routing between the connected networks. Routers does not need the transport layer, they work on the IP level only. The division between routers and hosts is not strict, because if a host have several interfaces, they can usually be configured to operate as a router too.

Each node on the Internet has a unique IP address. IP datagrams contain the IP address of the destination. The task of the routers is to find out the IP address of the next hop on the local network, and forward the packet to it. Sometimes the datagram is larger, than the maximum datagram that can be sent on the link (e.g. Ethernet has an 1500 bytes limit.). In this case the datagram is split into fragments and each fragment is transmitted independently. The destination host must collect all fragments, and assemble the datagram, before sending up the data to the transport layer.

The INET framework contains several modules to build the IPv4 network layer of hosts and routers:

- Ipv4 is the main module that implements RFC791. This module performs IP encapsulation/decapsulation, fragmentation and assembly, and routing of IP datagrams.
- The Ipv4RoutingTable is a helper module that manages the routing table of the node. It is queried by the Ipv4 module for best routes, and updated by the routing daemons implementing RIP, OSPF, Manet, etc. protocols.
- The Icmp module can be used to generate ICMP error packets. It also supports ICMP echo applications.
- The Arp module performs the dynamic translation of IP addresses to MAC addresses.
- The Igmpv2 module to generate and process multicast group membership reports.

These modules are assembled into a complete network layer module called Ipv4NetworkLayer. The Ipv4NetworkLayer module is present e.g. in StandardHost and Router.

The subsequent sections describe the IPv4 modules in detail.

8.2 IPv4

The IPv4 protocol is implemented by the Ipv4 module.

Its parameters include:

- `crcMode` TODO: @enum("declared", "computed") = default("declared");
- `procDelay` processing time of each incoming datagram.
- `timeToLive` default TTL of unicast datagrams.
- `multicastTimeToLive` default TTL of multicast datagrams.
- `fragmentTimeout` the maximum duration until fragments are kept in the fragment buffer.
- `limitedBroadcast` if `true`, then link-local broadcast datagrams are sent out through each interface, if the higher layer did not specify the outgoing interface.
- `useProxyARP` TODO: default(true);

8.3 IPv4 Routing Table

IPv4 route tables are represented with the Ipv4RoutingTable module. Hosts and routers normally contain one instance of this module. The Ipv4RoutingTable module does not send or receive messages. Instead, C++ methods are for querying and updating the table, as well as for unicast and multicast routing.

The Ipv4RoutingTable module has the following parameters:

- `routerId`: for routers, the router id using IPv4 address dotted notation; specify "auto" to select the highest interface address; should be left empty for hosts.
- `forwarding`: turns IP forwarding on/off. It is always `true` in a Router and is `false` by default in a StandardHost.
- `multicastForwarding`: turns multicast IP forwarding on/off. Default is `false`, should be set to `true` in multicast routers.

The preferred method for static initialization of routing tables is to use Ipv4NetworkConfigurator. While Ipv4RoutingTable can read the routes from a *routing file*, that is considered obsolete. Old routing files should be replaced with the XML configuration of Ipv4NetworkConfigurator. The *Network Autoconfiguration* chapter describes the format of the new configuration files.

8.4 ICMP

The Internet Control Message Protocol (ICMP) can be modeled with the Icmp module. ICMP is the error reporting and diagnostic mechanism of the Internet. It uses the services of IPv4, so it is a transport layer protocol, but unlike TCP or UDP, it is not used to transfer user data. It cannot be separated from IPv4, because the routing errors are reported by ICMP.

The Icmp module can be used to send error messages and ping request. It can also respond to incoming ICMP messages.

Each ICMP message is encapsulated within an IP datagram, so its delivery is unreliable.

8.5 ARP

The Address Resolution Protocol (ARP) is modeled with the Arp module. The ARP protocol is designed to translate a local protocol address to a hardware address. Although the ARP protocol can be used with several network protocol and hardware addressing schemes, in practice they are almost always IPv4 and 802.3 addresses. The Arp module only supports IPv4-to-MAC address translation, but not the opposite direction, Reverse ARP (RARP).

The address to be resolved can be either an IPv4 broadcast/multicast or a unicast address. The corresponding MAC addresses can be computed for broadcast and multicast addresses (RFC 1122, 6.4); unicast addresses are resolved using the ARP procotol.

If the MAC address is found in the ARP cache, then the packet is transmitted to the addressed interface immediately. Otherwise the packet is queued and an address resolution takes place.

For address resolution, ARP broadcasts a request frame on the network. In the request it publishes its own IP and MAC addresses, so each node in the local subnet can update their mapping. The node whose MAC address was requested will respond with an ARP frame containing its own MAC address directly to the node that sent the request. When the original node receives the ARP response, it updates its ARP cache and sends the delayed IP packet using the learned MAC address.

ARP resolution is initiated with a C++ call.

The module parameters of Arp are:

- `retryTimeout`: number of seconds ARP waits between retries to resolve an IPv4 address (default is 1s)
- `retryCount`: number of times ARP will attempt to resolve an IPv4 address (default is 3)
- `cacheTimeout`: number of seconds unused entries in the cache will time out (default is 120s)
- `proxyARP`: enables proxy ARP mode (default is `true`)
- `globalARP`: use global ARP cache (default is `false`)

8.6 IGMP

The Igmpv3 module implements the Internet Group Management Protocol (IGMP). IGMP is a communications protocol used by hosts and adjacent routers on IPv4 networks to establish multicast group memberships. IGMP is an integral part of IP multicast.

IGMP is responsible for distributing the information of multicast group memberships from hosts to routers. When an interface of a host joins to a multicast group, it will send an IGMP report on that interface to routers. It can also send reports when the interface leaves the multicast group, so it does not want to receive those multicast datagrams. The IGMP module of multicast routers processes these IGMP reports: it updates the list of groups, that has members on the link of the incoming message.

The IIgmp module interface defines the connections of IGMP modules. IGMP reports are transmitted by IP, so the module contains gates to be connected to the IP module (`ipIn/ipOut`). The IP module delivers packets with protocol number 2 to the IGMP module. However some multicast routing protocols (like DVMRP) also exchange routing information by sending IGMP messages, so they should be connected to the `routerIn/routerOut` gates of the IGMP module. The IGMP module delivers the IGMP messages not processed by itself to the connected routing module.

The Igmpv2 module implements version 2 of the IGMP protocol (RFC 2236). Next we describe its behaviour in host and routers in details. Note that multicast routers behaves as hosts too, i.e. they are sending reports to other routers when joining or leaving a multicast group.

8.6.1 Host behaviour

When an interface joins to a multicast group, the host will send a Membership Report immediately to the group address. This report is repeated after `unsolicitedReportInterval` to cover the possibility of the first report being lost.

When a host's interface leaves a multicast group, and it was the last host that sent a Membership Report for that group, it will send a Leave Group message to the all-routers multicast group (224.0.0.2).

This module also responds to IGMP Queries. When the host receives a Group-Specific Query on an interface that belongs to that group, then it will set a timer to a random value between 0 and Max Response Time of the Query. If the timer expires before the host observe a Membership Report sent by other hosts, then the host sends an IGMPv2 Membership Report. When the host receives a General Query on an interface, a timer is initialized and a report is sent for each group membership of the interface.

8.6.2 Router behaviour

Multicast routers maintains a list for each interface containing the multicast groups that have listeners on that interface. This list is updated when IGMP Membership Reports and Leave Group messages arrive, or when a timer expires since the last Query.

When multiple routers are connected to the same link, the one with the smallest IP address will be the Querier. When other routers observe that they are Non-Queriers (by receiving an IGMP Query with a lower source address), they stop sending IGMP Queries until `otherQuerierPresentInterval` elapsed since the last received query.

Routers periodically (`queryInterval`) send a General Query on each attached network for which this router is a Querier. On startup the router sends `startupQueryCount` queries separated by `startupQueryInterval`. A General Query has unspecified Group Address field, a Max Response Time field set to `queryResponseInterval`, and is sent to the all-systems multicast address (224.0.0.1).

When a router receives a Membership Report, it will add the reported group to the list of multicast group memberships. At the same time it will set a timer for the membership to `groupMembershipInterval`. Repeated reports restart the timer. If the timer expires, the router assumes that the group has no local members, and multicast traffic is no more forwarded to that interface.

When a Querier receives a Leave Group message for a group, it sends a Group-Specific Query to the group being left. It repeats the Query `lastMemberQueryCount` times in separated by `lastMemberQueryInterval` until a Membership Report is received. If no Report received, then the router assumes that the group has no local members.

8.6.3 Parameters

The following parameters have effects in both hosts and routers:

- `enabled` if `false` then the IGMP module never sends any message and discards incoming messages. Default is `true`.

The following parameters are only used in hosts:

- `unsolicitedReportInterval` the time between repetitions of a host's initial report of membership in a group. Default is 10s.

Router timeouts are configured by these parameters:

- `robustnessVariable` the IGMP is robust to `robustnessVariable`-1 packet losses. Default is 2.
- `queryInterval` the interval between General Queries sent by a Querier. Default is 125s.
- `queryResponseInterval` the Max Response Time inserted into General Queries

- `groupMembershipInterval` the amount of time that must pass before a multicast router decides there are no more members of a group on a network. Fixed to `robustnessVariable` * `queryInterval` + `queryResponseInterval`.
- `otherQuerierPresentInterval` the length of time that must pass before a multicast router decides that there is no longer another multicast router which should be the querier. Fixed to `robustnessVariable` * `queryInterval` + `queryResponseInterval` / 2.
- `startupQueryInterval` the interval between General Queries sent by a Querier on startup. Default is `queryInterval` / 4.
- `startupQueryCount` the number of Queries sent out on startup, separated by the `startupQueryInterval`. Default is `robustnessVariable`.
- `lastMemberQueryInterval` the Max Response Time inserted into Group-Specific Queries sent in response to Leave Group messages, and is also the amount of time between Group-Specific Query messages. Default is 1s.
- `lastMemberQueryCount` the number of Group-Specific Queries sent before the router assumes there are no local members. Default is `robustnessVariable`.

CHAPTER

NINE

IPV6 AND MOBILE IPV6

9.1 Overview

Similarly to IPv4, IPv6 support is implemented by several cooperating modules. The base protocol is in the Ipv6 module, which relies on the Ipv6RoutingTable to get access to the routes. Interface configuration (address, state, timeouts, etc.) is held in the node's InterfaceTable.

The Ipv6NeighbourDiscovery module implements all tasks associated with neighbour discovery and stateless address autoconfiguration. The data structures themselves (destination cache, neighbour cache, prefix list) are kept in Ipv6RoutingTable. The rest of ICMPv6's functionality, such as error messages, echo request/reply, etc.) is implemented in Icmpv6.

Mobile IPv6 support has been contributed to INET by the xMIPv6 project. The main module is xMIPv6, which implements Fast MIPv6, Hierarchical MIPv6 and Fast Hierarchical MIPv6 (thus, $x \in F, H, FH$). The binding cache and related data structures are kept in the BindingCache module.

CHAPTER

TEN

OTHER NETWORK PROTOCOLS

10.1 Overview

Network layer protocols in INET are not restricted to IPv4 and IPv6. INET nodes such as Router and StandardHost can be configured to use an alternative network layer protocols instead of, or in addition to, IPv4 and IPv6.

Node models contain three optional network layers that can be individually turned on or off:

```
ipv4: <default("Ipv4NetworkLayer")> like INetworkLayer if hasIpv4;
ipv6: <default("Ipv6NetworkLayer")> like INetworkLayer if hasIpv6;
generic: <default("")> like INetworkLayer if hasGn;
```

In the default configuration, only IPv4 is turned on. If you want to use an alternative network layer protocol instead of IPv4/IPv6, your configuration will look something like this:

```
**.hasIpv4 = false
**.hasIpv6 = false
**.hasGn = true
**.generic.typename = "WiseRouteNetworkLayer"
```

The list of alternative network layers includes:

- SimpleNetworkLayer is a generic network layer where the concrete protocol type is a parameter
- NextHopNetworkLayer is a network layer specialized for the "Next-Hop Forwarding Protocol", an abstract implementation of the next-hop routing concept
- WiseRouteNetworkLayer is specialized for the Wise Route protocol

The list of network layer protocols that can be plugged into SimpleNetworkLayer includes:

- Flooding implements controlled flooding
- WiseRoute implements Wise Route, a convergecasting protocol for wireless sensor networks
- ProbabilisticBroadcast implements a multi-hop ad-hoc data dissemination protocol
- AdaptiveProbabilisticBroadcast is a variant of the previous one

In addition to the network layer protocol, SimpleNetworkLayer includes an instance of GlobalArp for address resolution, and an instance of EchoProtocol, a module type that implements a simple *ping*-like protocol.

All the above network protocols can work with IPv4 addresses, IPv6 addresses, use MAC address as network address (this is sometimes useful in WSNs), or use sythetic addresses that only make sense within the simulation.[1]

In apps, you need to specify which network layer protocol you want to use. For example:

```
**.app[*].networkProtocol = "flood"
```

[1] This is possible because the implementation of these modules simply use the `L3Address` C++ class, which is a variant type capable of holding several types of L3 addresses.

10.2 Protocols

10.2.1 Flooding

Flooding is a simple flooding protocol for network-level broadcast. It remembers already broadcast messages, and does not rebroadcast them if it gets another copy of that message.

10.2.2 ProbabilisticBroadcast

ProbabilisticBroadcast is a multi-hop ad-hoc data dissemination protocol based on probabilistic broadcast.

This method reduces the number of packets sent on the channel (reducing the broadcast storm problem) at the risk of some nodes not receiving the data. It is particularly interesting for mobile networks.

The transmission probability for each attempt, the time between two transmission attempts, the maximum number of broadcast transmissions of a packet, and some other settings are parameters.

10.2.3 AdaptiveProbabilisticBroadcast

AdaptiveProbabilisticBroadcast is a variant of ProbabilisticBroadcast that automatically adjusts transmission probabilities depending on the estimated number of neighbours.

10.2.4 WiseRoute

WiseRoute implements Wise Route, a simple loop-free routing algorithm that builds a routing tree from a central network point, designed for sensor networks and convergecast traffic (WIreless SEnsor routing).

The sink (the device at the center of the network) broadcasts a route building message. Each network node that receives it selects the sink as parent in the routing tree, and rebroadcasts the route building message. This procedure maximizes the probability that all network nodes can join the network, and avoids loops.

The `sinkAddress` parameter specifies the sink network address, `rssiThreshold` is a threshold to avoid using bad links (with too low RSSI values) for routing, and `routeFloodsInterval` should be set to zero for all nodes except the sink. Each `routeFloodsInterval`, the sink restarts the tree building procedure. Set it to a large value if you do not want the tree to be rebuilt.

10.2.5 NextHopForwarding

The NextHopForwarding module is an implementation of the next-hop forwarding concept. (It can be thought of as an abstracted version of IP.)

The protocol needs an additional module, a NextHopRoutingTable for its operation. The routing table module is included in the NextHopNetworkLayer compound module.

10.3 Address Types

The following address types are available:

- IPv4 address
- IPv6 address
- MAC address
- module ID
- module path

Protocols described in this chapter work with "generic" L3 addresses, they can use any address type.

When choosing IPv4 addresses, an Ipv4NetworkConfigurator global instance can be used to assign addresses to network interfaces. (Note that Ipv4NetworkConfigurator also needs a per-node instance of Ipv4NodeConfigurator for it to work.)

10.4 Address Resolution

Address resolution is done by GlobalArp. If the address type is IPv4, Arp can be used instead of GlobalArp.

CHAPTER

ELEVEN

NETWORK AUTOCONFIGURATION

11.1 Overview

This chapter describes static autoconfiguration of networks.

11.2 Configuring IPv4 Networks

An IPv4 network is composed of several nodes like hosts, routers, switches, hubs, Ethernet buses, or wireless access points. The nodes having a IPv4 network layer (hosts and routers) should be configured at the beginning of the simulation. The configuration assigns IP addresses to the nodes, and fills their routing tables. If multicast forwarding is simulated, then the multicast routing tables also must be filled in.

The configuration can be manual (each address and route is fully specified by the user), or automatic (addresses and routes are generated by a configurator module at startup).

Before version 1.99.4, INET offered Ipv4FlatNetworkConfigurator for automatic, and routing files for manual configuration. Both configuration methods had serious limitations, so a new configurator has been added in version 1.99.4: Ipv4NetworkConfigurator. This configurator supports both fully manual and fully automatic configuration. It can also be used with partially specified manual configurations, the configurator fills in the gaps automatically.

The next section describes the usage of Ipv4NetworkConfigurator. The legacy solutions Ipv4FlatNetworkConfigurator and routing files are described in subsequent sections.

11.2.1 Ipv4NetworkConfigurator

The Ipv4NetworkConfigurator assigns IP addresses and sets up static routing for an IPv4 network.

It assigns per-interface IP addresses, strives to take subnets into account, and can also optimize the generated routing tables by merging routing entries.

Hierarchical routing can be set up by using only a fraction of configuration entries compared to the number of nodes. The configurator also does routing table optimization that significantly decreases the size of routing tables in large networks.

The configuration is performed in stage 2 of the initialization. At this point interface modules (e.g. PPP) has already registered their interface in the interface table. If an interface is named `ppp[0]`, then the corresponding interface entry is named `ppp0`. This name can be used in the config file to refer to the interface.

The configurator goes through the following steps:

1. Builds a graph representing the network topology. The graph will have a vertex for every module that has a `@node` property (this includes hosts, routers, and L2 devices like switches, access points, Ethernet hubs, etc.) It also assigns weights to vertices and edges that will be used by the shortest path algorithm when setting up routes. Weights will be infinite for IP nodes that have IP forwarding disabled (to prevent routes from transiting them), and zero for all other nodes (routers and and L2 devices). Edge weights are chosen to be inversely proportional to the bitrate of the link, so that the configurator prefers connections with higher

bandwidth. For internal purposes, the configurator also builds a table of all "links" (the link data structure consists of the set of network interfaces that are on the same point-to-point link or LAN)

2. Assigns IP addresses to all interfaces of all nodes. The assignment process takes into consideration the addresses and netmasks already present on the interfaces (possibly set in earlier initialize stages), and the configuration provided in the XML format (described below). The configuration can specify "templates" for the address and netmask, with parts that are fixed and parts that can be chosen by the configurator (e.g. "10.0.x.x"). In the most general case, the configurator is allowed to choose any address and netmask for all interfaces (which results in automatic address assignment). In the most constrained case, the configurator is forced to use the requested addresses and netmasks for all interfaces (which translates to manual address assignment). There are many possible configuration options between these two extremums. The configurator assigns addresses in a way that maximizes the number of nodes per subnet. Once it figures out the nodes that belong to a single subnet it, will optimize for allocating the longest possible netmask. The configurator might fail to assign netmasks and addresses according to the given configuration parameters; if that happens, the assignment process stops and an error is signalled.
3. Adds the manual routes that are specified in the configuration.
4. Adds static routes to all routing tables in the network. The configurator uses Dijkstra's weighted shortest path algorithm to find the desired routes between all possible node pairs. Then it will populate the routing tables with entries to allow accessing all destination Interfaces in the network. The configurator can be safely instructed to add default routes where applicable, significantly reducing the size of the host routing tables. It can also add subnet routes instead of interface routes further reducing the size of routing tables. Turning on this option requires careful design to avoid having IP addresses from the same subnet on different links. CAVEAT: Using manual routes and static route generation together may have unwanted side effects, because route generation ignores manual routes.
5. Then it optimizes the routing tables for size. This optimization allows configuring larger networks with smaller memory footprint and makes the routing table lookup faster. The resulting routing table might be different in that it will route packets that the original routing table did not. Nevertheless the following invariant holds: any packet routed by the original routing table (has matching route) will still be routed the same way by the optimized routing table.
6. Finally it dumps the requested results of the configuration. It can dump network topology, assigned IP addresses, routing tables and its own configuration format.

The module can dump the result of the configuration in the XML format which it can read. This is useful to save the result of a time consuming configuration (large network with optimized routes), and use it as the config file of subsequent runs.

Network topology graph

The network topology graph is constructed from the nodes of the network. The node is a module having a `@node` property (this includes hosts, routers, and L2 devices like switches, access points, Ethernet hubs, etc.). An IP node is a node that contains an InterfaceTable and a Ipv4RoutingTable. A router is an IP node that has multiple network interfaces, and IP forwarding is enabled in its routing table module. In multicast routers the `forwardMulticast` parameter is also set to `true`.

A link is a set of interfaces that can send datagrams to each other without intervening routers. Each interface belongs to exactly one link. For example two interface connected by a point-to-point connection forms a link. Ethernet interfaces connected via buses, hubs or switches. The configurator identifies links by discovering the connections between the IP nodes, buses, hubs, and switches.

Wireless links are identified by the `ssid` or `accessPointAddress` parameter of the 802.11 management module. Wireless interfaces whose node does not contain a management module are supposed to be on the same wireless link. Wireless links can also be configured in the configuration file of Ipv4NetworkConfigurator:

```
<config>
  <wireless hosts="area1.*" interfaces="wlan*">
</config>
```

puts wlan interfaces of the specified hosts into the same wireless link.

If a link contains only one router, it is marked as the gateway of the link. Each datagram whose destination is outside the link must go through the gateway.

Address assignment

Addresses can be set up manually by giving the address and netmask for each IP node. If some part of the address or netmask is unspecified, then the configurator can fill them automatically. Unspecified fields are given as an "x" character in the dotted notation of the address. For example, if the address is specified as 192.168.1.1 and the netmask is 255.255.255.0, then the node address will be 192.168.1.1 and its subnet is 192.168.1.0. If it is given as 192.168.x.x and 255.255.x.x, then the configurator chooses a subnet address in the range of 192.168.0.0 - 192.168.255.252, and an IP address within the chosen subnet. (The maximum subnet mask is 255.255.255.252 allows 2 nodes in the subnet.)

The following configuration generates network addresses below the 10.0.0.0 address for each link, and assign unique IP addresses to each host:

```
<config>
  <interface hosts="*" address="10.x.x.x" netmask="255.x.x.x"/>
</config>
```

The configurator tries to put nodes on the same link into the same subnet, so its enough to configure the address of only one node on each link.

The following example configures a hierarchical network in a way that keeps routing tables small.

```
<config>
  <interface hosts="area11.lan1.*" address="10.11.1.x" netmask="255.255.255.x"/>
  <interface hosts="area11.lan2.*" address="10.11.2.x" netmask="255.255.255.x"/>
  <interface hosts="area12.lan1.*" address="10.12.1.x" netmask="255.255.255.x"/>
  <interface hosts="area12.lan2.*" address="10.12.2.x" netmask="255.255.255.x"/>
  <interface hosts="area*.router*" address="10.x.x.x" netmask="x.x.x.x"/>
  <interface hosts="*" address="10.x.x.x" netmask="255.x.x.0"/>
</config>
```

The XML configuration must contain exactly one `<config>` element. Under the root element there can be multiple of the following elements:

The interface element provides configuration parameters for one or more interfaces in the network. The selector attributes limit the scope where the interface element has effects. The parameter attributes limit the range of assignable addresses and netmasks. The `<interface>` element may contain the following attributes:

- `@hosts` Optional selector attribute that specifies a list of host name patterns. Only interfaces in the specified hosts are affected. The pattern might be a full path starting from the network, or a module name anywhere in the hierarchy, and other patterns similar to ini file keys. The default value is "*" that matches all hosts. e.g. "subnet.client*" or "host* router[0..3]" or "area*.*.host[0]"
- `@names` Optional selector attribute that specifies a list of interface name patterns. Only interfaces with the specified names are affected. The default value is "*" that matches all interfaces. e.g. "eth* ppp0" or "*"
- `@towards` Optional selector attribute that specifies a list of host name patterns. Only interfaces connected towards the specified hosts are affected. The specified name will be matched against the names of hosts that are on the same LAN with the one that is being configured. This works even if there's a switch between the configured host and the one specified here. For wired networks it might be easier to specify this parameter instead of specifying the interface names. The default value is "*". e.g. "ap" or "server" or "client*"
- `@among` Optional selector attribute that specifies a list of host name patterns. Only interfaces in the specified hosts connected towards the specified hosts are affected. The 'among="X Y Z"' is same as 'hosts="X Y Z" towards="X Y Z"'.
- `@address` Optional parameter attribute that limits the range of assignable addresses. Wildcards are allowed with using 'x' as part of the address in place of a byte. Unspecified parts will be filled automatically

by the configurator. The default value "" means that the address will not be configured. Unconfigured interfaces still have allocated addresses in their subnets allowing them to become configured later very easily. e.g. "192.168.1.1" or "10.0.x.x"

- `@netmask` Optional parameter attribute that limits the range of assignable netmasks. Wildcards are allowed with using 'x' as part of the netmask in place of a byte. Unspecified parts will be filled automatically be the configurator. The default value "" means that any netmask can be configured. e.g. "255.255.255.0" or "255.255.x.x" or "255.255.x.0"
- `@mtu` number Optional parameter attribute to set the MTU parameter in the interface. When unspecified the interface parameter is left unchanged.
- `@metric` number Optional parameter attribute to set the Metric parameter in the interface. When unspecified the interface parameter is left unchanged.

Wireless interfaces can similarly be configured by adding `<wireless>` elements to the configuration. Each `<wireless>` element with a different id defines a separate subnet.

- `@id` (optional) identifies wireless network, unique value used if missed
- `@hosts` Optional selector attribute that specifies a list of host name patterns. Only interfaces in the specified hosts are affected. The default value is "*" that matches all hosts.
- `@interfaces` Optional selector attribute that specifies a list of interface name patterns. Only interfaces with the specified names are affected. The default value is "*" that matches all interfaces.

Multicast groups

Multicast groups can be configured by adding `<multicast-group>` elements to the configuration file. Interfaces belongs to a multicast group will join to the group automatically.

For example,

```
<config>
  <multicast-group hosts="router*" interfaces="eth*" address="224.0.0.5"/>
</config>
```

adds all Ethernet interfaces of nodes whose name starts with "router" to the 224.0.0.5 multicast group.

The `<multicast-group>` element has the following attributes:

- `@hosts` Optional selector attribute that specifies a list of host name patterns. Only interfaces in the specified hosts are affected. The default value is "*" that matches all hosts.
- `@interfaces` Optional selector attribute that specifies a list of interface name patterns. Only interfaces with the specified names are affected. The default value is "*" that matches all interfaces.
- `@towards` Optional selector attribute that specifies a list of host name patterns. Only interfaces connected towards the specified hosts are affected. The default value is "*".
- `@among` Optional selector attribute that specifies a list of host name patterns. Only interfaces in the specified hosts connected towards the specified hosts are affected. The 'among="X Y Z"' is same as 'hosts="X Y Z" towards="X Y Z"'.
- `@address` Mandatory parameter attribute that specifies a list of multicast group addresses to be assigned. Values must be selected from the valid range of multicast addresses. e.g. "224.0.0.1 224.0.1.33"

Manual route configuration

The Ipv4NetworkConfigurator module allows the user to fully specify the routing tables of IP nodes at the beginning of the simulation.

The `<route>` elements of the configuration add a route to the routing tables of selected nodes. The element has the following attributes:

- `@hosts` Optional selector attribute that specifies a list of host name patterns. Only routing tables in the specified hosts are affected. The default value "" means all hosts will be affected. e.g. "host* router[0..3]"
- `@destination` Optional parameter attribute that specifies the destination address in the route (L3AddressResolver syntax). The default value is "*". e.g. "192.168.1.1" or "subnet.client[3]" or "subnet.server(ipv4)" or "*"
- `@netmask` Optional parameter attribute that specifies the netmask in the route. The default value is "*". e.g. "255.255.255.0" or "/29" or "*"
- `@gateway` Optional parameter attribute that specifies the gateway (next-hop) address in the route (L3AddressResolver syntax). When unspecified the interface parameter must be specified. The default value is "*". e.g. "192.168.1.254" or "subnet.router" or "*"
- `@interface` Optional parameter attribute that specifies the output interface name in the route. When unspecified the gateway parameter must be specified. This parameter has no default value. e.g. "eth0"
- `@metric` Optional parameter attribute that specifies the metric in the route. The default value is 0.

Multicast routing tables can similarly be configured by adding `<multicast-route>` elements to the configuration.

- `@hosts` Optional selector attribute that specifies a list of host name patterns. Only routing tables in the specified hosts are affected. e.g. "host* router[0..3]"
- `@source` Optional parameter attribute that specifies the address of the source network. The default value is "*" that matches all sources.
- `@netmask` Optional parameter attribute that specifies the netmask of the source network. The default value is "*" that matches all sources.
- `@groups` Optional List of IPv4 multicast addresses specifying the groups this entry applies to. The default value is "*" that matches all multicast groups. e.g. "225.0.0.1 225.0.1.2".
- `@metric` Optional parameter attribute that specifies the metric in the route.
- `@parent` Optional parameter attribute that specifies the name of the interface the multicast datagrams are expected to arrive. When a datagram arrives on the parent interface, it will be forwarded towards the child interfaces; otherwise it will be dropped. The default value is the interface on the shortest path towards the source of the datagram.
- `@children` Mandatory parameter attribute that specifies a list of interface name patterns:
  - a name pattern (e.g. "ppp*") matches the name of the interface
  - a 'towards' pattern (starting with ">", e.g. ">router*") matches the interface by naming one of the neighbour nodes on its link.

  Incoming multicast datagrams are forwarded to each child interface except the one they arrived in.

The following example adds an entry to the multicast routing table of `router1`, that intsructs the routing algorithm to forward multicast datagrams whose source is in the 10.0.1.0 network and whose destinatation address is 225.0.0.1 to send on the `eth1` and `eth2` interfaces assuming it arrived on the `eth0` interface:

```
<multicast-route hosts="router1" source="10.0.1.0" netmask="255.255.255.0"
                 groups="225.0.0.1" metric="10"
                 parent="eth0" children="eth1 eth2"/>
```

Automatic route configuration

If the `addStaticRoutes` parameter is true, then the configurator adds static routes to all routing tables.

The configurator uses Dijkstra's weighted shortest path algorithm to find the desired routes between all possible node pairs. As a result, each routing table will be populated with entries to allow accesssing all destination interfaces in the network directly or indirectly.

The configurator can be safely instructed to add default routes where applicable, significantly reducing the size of the host routing tables. It can also add subnet routes instead of interface routes further reducing the size of routing tables. Turning on this option requires careful design to avoid having IP addresses from the same subnet on different links.

Caution: Using manual routes and static route generation together may have unwanted side effects, because route generation ignores manual routes. Therefore if the configuration file contains manual routes, then the `addStaticRoutes` parameter should be set to `false`.

Route optimization

If the `optimizeRoutes` parameter is `true` then the configurator tries to optimize the routing table for size. This optimization allows configuring larger networks with smaller memory footprint and makes the routing table lookup faster.

The optimization is performed by merging routes whose gateway and outgoing interface is the same by finding a common prefix that matches only those routes. The resulting routing table might be different in that it will route packets that the original routing table did not. Nevertheless the following invariant holds: any packet routed by the original routing table (has matching route) will still be routed the same way by the optimized routing table.

Parameters

This list summarize the parameters of the Ipv4NetworkConfigurator:

- `config`: XML configuration parameters for IP address assignment and adding manual routes.
- `assignAddresses`: assign IP addresses to all interfaces in the network
- `assignDisjunctSubnetAddresses`: avoid using the same address prefix and netmask on different links when assigning IP addresses to interfaces
- `addStaticRoutes`: add static routes to the routing tables of all nodes to route to all destination interfaces (only where applicable; turn off when config file contains manual routes)
- `addDefaultRoutes`: add default routes if all routes from a source node go through the same gateway (used only if addStaticRoutes is true)
- `addSubnetRoutes`: add subnet routes instead of destination interface routes (only where applicable; used only if addStaticRoutes is true)
- `optimizeRoutes`: optimize routing tables by merging routes, the resulting routing table might route more packets than the original (used only if addStaticRoutes is true)
- `dumpTopology`: if true, then the module prints extracted network topology
- `dumpAddresses`: if true, then the module prints assigned IP addresses for all interfaces
- `dumpRoutes`: if true, then the module prints configured and optimized routing tables for all nodes to the module output
- `dumpConfig`: name of the file, write configuration into the given config file that can be fed back to speed up subsequent runs (network configurations)

11.2.2 Ipv4FlatNetworkConfigurator (Legacy)

The Ipv4FlatNetworkConfigurator module configures IP addresses and routes of IP nodes of a network. All assigned addresses share a common subnet prefix, the network topology will be ignored. Shortest path routes are also generated from any node to any other node of the network. The Gateway (next hop) field of the routes is not filled in by these configurator, so it relies on proxy ARP if the network spans several LANs. It does not perform routing table optimization (i.e. merging similar routes into a single, more general route.)

Warning: Ipv4FlatNetworkConfigurator is considered legacy, do not use it for new projects.

The Ipv4FlatNetworkConfigurator module configures the network when it is initialized. The configuration is performed in stage 2, after interface tables are filled in. Do not use a Ipv4FlatNetworkConfigurator module together with static routing files, because they can iterfere with the configurator.

The Ipv4FlatNetworkConfigurator searches each IP nodes of the network. (IP nodes are those modules that have the @node NED property and has a Ipv4RoutingTable submodule named "routingTable"). The configurator then assigns IP addresses to the IP nodes, controlled by the following module parameters:

- `netmask` common netmask of the addresses (default is 255.255.0.0)
- `networkAddress` higher bits are the network part of the addresses, lower bits should be 0. (default is 192.168.0.0)

With the default parameters the assigned addresses are in the range 192.168.0.1 - 192.168.255.254, so there can be maximum 65534 nodes in the network. The same IP address will be assigned to each interface of the node, except the loopback interface which always has address 127.0.0.1 (with 255.0.0.0 mask).

After assigning the IP addresses, the configurator fills in the routing tables. There are two kind of routes:

- default routes: for nodes that has only one non-loopback interface a route is added that matches with any destination address (the entry has 0.0.0.0 `host` and `netmask` fields). These are remote routes, but the gateway address is left unspecified. The delivery of the datagrams rely on the proxy ARP feature of the routers.
- direct routes following the shortest paths: for nodes that has more than one non-loopback interface a separate route is added to each IP node of the network. The outgoing interface is chosen by the shortest path to the target node. These routes are added as direct routes, even if there is no direct link with the destination. In this case proxy ARP is needed to deliver the datagrams.

Note: This configurator does not try to optimize the routing tables. If the network contains n nodes, the size of all routing tables will be proportional to n^2, and the time of the lookup of the best matching route will be proportional to n.

11.2.3 Routing Files (Legacy)

Routing files are files with `.irt` or `.mrt` extension, and their names are passed in the `routingFile` parameter to Ipv4RoutingTable modules.

Routing files may contain network interface configuration and static routes. Both are optional. Network interface entries in the file configure existing interfaces; static routes are added to the route table.

Warning: *Routing files* are considered legacy, use do not use them for new projects. Their contents can be expressed in Ipv4NetworkConfigurator config files.

Interfaces themselves are represented in the simulation by modules (such as the PPP module). Modules automatically register themselves with appropriate defaults in the IPv4RoutingTable, and entries in the routing file refine

(overwrite) these settings. Interfaces are identified by names (e.g. ppp0, ppp1, eth0) which are normally derived from the module's name: a module called "ppp[2]" in the NED file registers itself as interface ppp2.

An example routing file (copied here from one of the example simulations):

```
ifconfig:

# ethernet card 0 to router
name: eth0   inet_addr: 172.0.0.3   MTU: 1500   Metric: 1  BROADCAST MULTICAST
Groups: 225.0.0.1:225.0.1.2:225.0.2.1

# Point to Point link 1 to Host 1
name: ppp0   inet_addr: 172.0.0.4   MTU: 576   Metric: 1

ifconfigend.

route:
172.0.0.2   *           255.255.255.255  H  0   ppp0
172.0.0.4   *           255.255.255.255  H  0   ppp0
default:    10.0.0.13   0.0.0.0          G  0   eth0

225.0.0.1   *           255.255.255.255  H  0   ppp0
225.0.1.2   *           255.255.255.255  H  0   ppp0
225.0.2.1   *           255.255.255.255  H  0   ppp0

225.0.0.0   10.0.0.13   255.0.0.0        G  0   eth0

routeend.
```

The `ifconfig...ifconfigend.` part configures interfaces, and `route..routeend.` part contains static routes. The format of these sections roughly corresponds to the output of the `ifconfig` and `netstat -rn` Unix commands.

An interface entry begins with a `name:` field, and lasts until the next `name:` (or until `ifconfigend.`). It may be broken into several lines.

Accepted interface fields are:

- `name:` - arbitrary interface name (e.g. eth0, ppp0)
- `inet_addr:` - IP address
- `Mask:` - netmask
- `Groups:` Multicast groups. 224.0.0.1 is added automatically, and 224.0.0.2 also if the node is a router (IPForward==true).
- `MTU:` - MTU on the link (e.g. Ethernet: 1500)
- `Metric:` - integer route metric
- flags: `BROADCAST`, `MULTICAST`, `POINTTOPOINT`

The following fields are parsed but ignored: `Bcast`, `encap`, `HWaddr`.

Interface modules set a good default for MTU, Metric (as $2 * 10^9$/bitrate) and flags, but leave `inet_addr` and `Mask` empty. `inet_addr` and `mask` should be set either from the routing file or by a dynamic network configuration module.

The route fields are:

```
Destination  Gateway  Netmask  Flags  Metric Interface
```

`Destination`, `Gateway` and `Netmask` have the usual meaning. The `Destination` field should either be an IP address or "default" (to designate the default route). For `Gateway`, `*` is also accepted with the meaning `0.0.0.0`.

`Flags` denotes route type:

- *H* "host": direct route (directly attached to the router), and
- *G* "gateway": remote route (reached through another router)

`Interface` is the interface name, e.g. `eth0`.

Important: The meaning of the routes where the destination is a multicast address has been changed in version 1.99.4. Earlier these entries was used both to select the outgoing interfaces of multicast datagrams sent by the higher layer (if multicast interface was otherwise unspecified) and to select the outgoing interfaces of datagrams that are received from the network and forwarded by the node.

From version 1.99.4 multicast routing applies reverse path forwarding. This requires a separate routing table, that can not be populated from the old routing table entries. Therefore simulations that use multicast forwarding can not use the old configuration files, they should be migrated to use an Ipv4NetworkConfigurator instead.

Some change is needed in models that use link-local multicast too. Earlier if the IP module received a datagram from the higher layer and multiple routes was given for the multicast group, then IP sent a copy of the datagram on each interface of that routes. From version 1.99.4, only the first matching interface is used (considering longest match). If the application wants to send the multicast datagram on each interface, then it must explicitly loop and specify the multicast interface.

11.3 Configuring Layer 2

The L2NetworkConfigurator module allows configuring network scenarios at layer 2. The STP/RTP-related parameters such as link cost, port priority and the "is-edge" flag can be configured with XML files.

This module is similar to Ipv4NetworkConfigurator. It supports the selector attributes `@hosts`, `@names`, `@towards`, `@among`, and they behave similarly to its Ipv4NetworkConfigurator equivalent. The `@ports` selector is also supported, for configuring per-port parameters.

The following example configures port 5 (if it exists) on all switches, and sets cost=19 and priority=32768:

```
<config>
  <interface hosts='**' ports='5' cost='19' priority='32768'/>
</config>
```

For more information about the usage of the selector attributes see Ipv4NetworkConfigurator.

CHAPTER

TWELVE

INTERNET ROUTING

12.1 Overview

INET Framework has models for several internet routing protocols, including RIP, OSPF and BGP.

The easiest way to add routing to a network is to use the Router NED type for routers. Router contains a conditional instance for each of the above protocols. These submodules can be enabled by setting the `hasRip`, `hasOspf` and/or `hasBgp` parameters to `true`.

Example:

```
**.hasRip = true
```

There are also NED types called RipRouter, OspfRouter, BgpRouter, which are all Router's with appropriate routing protocol enabled.

12.2 RIP

RIP (Routing Information Protocol) is a distance-vector routing protocol which employs the hop count as a routing metric. RIP prevents routing loops by implementing a limit on the number of hops allowed in a path from source to destination. RIP uses the *split horizon with poison reverse* technique to work around the "count-to-infinity" problem.

The Rip module implements distance vector routing as specified in RFC 2453 (RIPv2) and RFC 2080 (RIPng). The behavior can be selected by setting the `mode` parameter to either `"RIPv2"` or `"RIPng"`. Protocol configuration such as link metrics and per-interface operation mode (such as whether RIP is enabled on the interface, and whether to use split horizon) can be specified in XML using the `ripConfig` parameter.

The following example configures a Router module to use RIPv2:

```
**.hasRip = true
**.mode = "RIPv2"
**.ripConfig = xmldoc("RIPConfig.xml")
```

The configuration file specifies the per interface parameters. Each `<interface>` element configures one or more interfaces; the `hosts`, `names`, `towards`, `among` attributes select the configured interfaces (in a similar way as with Ipv4NetworkConfigurator). See the *Network Autoconfiguration* chapter for further information.

Additional attributes:

- `metric`: metric assigned to the link, default value is 1. This value is added to the metric of a learned route, received on this interface. It must be an integer in the [1,15] interval.
- `mode`: mode of the interface.

The mode attribute can be one of the following:

- `NoRIP`: no RIP messages are sent or received on this interface.

- `NoSplitHorizon`: no split horizon filtering; send all routes to neighbors.
- `SplitHorizon`: do not sent routes whose next hop is the neighbor.
- `SplitHorizonPoisenedReverse` (default): if the next hop is the neighbor, then set the metric of the route to infinity.

The following example sets the link metric between router `R1` and `RB` to 2, while all other links will have a metric of 1.

```
<RIPConfig>
  <interface among="R1 RB" metric="2"/>
  <interface among="R? R?" metric="1"/>
</RIPConfig>
```

12.3 OSPF

OSPF (Open Shortest Path First) is a routing protocol for IP networks. It uses a link state routing (LSR) algorithm and falls into the group of interior gateway protocols (IGPs), operating within a single autonomous system (AS).

OspfRouter is a Router with the OSPF protocol enabled.

The Ospfv2 module implements OSPF protocol version 2. Areas and routers can be configured using an XML file specified by the `ospfConfig` parameter. Various parameters for the network interfaces can be specified also in the XML file or as a parameter of the Ospfv2 module.

```
**.ospf.ospfConfig = xmldoc("ASConfig.xml")
**.ospf.helloInterval = 12s
**.ospf.retransmissionInterval = 6s
```

The `<OSPFASConfig>` root element may contain `<Area>` and `<Router>` elements with various attributes specifying the parameters for the network interfaces. Most importantly `<Area>` contains `<AddressRange>` elements enumerating the network addresses that should be advertized by the protocol. Also `<Router>` elements may contain data for configuring various pont-to-point or broadcast interfaces.

```
<?xml version="1.0"?>
<OSPFASConfig xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"␣
↪xsi:schemaLocation="OSPF.xsd">
  <!-- Areas -->
  <Area id="0.0.0.0">
    <AddressRange address="H1" mask="H1" status="Advertise" />
    <AddressRange address="H2" mask="H2" status="Advertise" />
    <AddressRange address="R1>R2" mask="R1>R2" status="Advertise" />
    <AddressRange address="R2>R1" mask="R2>R1" status="Advertise" />
  </Area>
  <!-- Routers -->
  <Router name="R1" RFC1583Compatible="true">
    <BroadcastInterface ifName="eth0" areaID="0.0.0.0" interfaceOutputCost="1"␣
↪routerPriority="1" />
    <PointToPointInterface ifName="eth1" areaID="0.0.0.0" interfaceOutputCost="2" /
↪>
  </Router>
  <Router name="R2" RFC1583Compatible="true">
    <PointToPointInterface ifName="eth0" areaID="0.0.0.0" interfaceOutputCost="2" /
↪>
    <BroadcastInterface ifName="eth1" areaID="0.0.0.0" interfaceOutputCost="1"␣
↪routerPriority="2" />
  </Router>
</OSPFASConfig>
```

12.4 BGP

BGP (Border Gateway Protocol) is a standardized exterior gateway protocol designed to exchange routing and reachability information among autonomous systems (AS) on the Internet.

BgpRouter is a Router with the BGP protocol enabled.

The Bgp module implements BGP Version 4. The model implements RFC 4271, with some limitations. Autonomous Systems and rules can be configured in an XML file that can be specified in the `bgpConfig` parameter.

```
**.bgpConfig = xmldoc("BGPConfig.xml")
```

The configuration file may contain `<TimerParams>`, `<AS>` and `Session` elements at the top level.

- `<TimerParams>`: allows specifying various timing parameters for the routers.
- `<AS>`: defines Autonomous Systems, routers and rules to be applied.
- `<Session>`: specifies open sessions between edge routers. It must contain exactly two `<Router exterAddr="x.x.x.x"/>` elements.

```
<BGPConfig xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
  xsi:schemaLocation="BGP.xsd">

  <TimerParams>
    <connectRetryTime> 120 </connectRetryTime>
    <holdTime> 180 </holdTime>
    <keepAliveTime> 60 </keepAliveTime>
    <startDelay> 15 </startDelay>
  </TimerParams>

  <AS id="60111">
    <Router interAddr="172.1.10.255"/> <!--Router A1-->
    <Router interAddr="172.1.20.255"/> <!--Router A2-->
  </AS>

  <AS id="60222">
    <Router interAddr="172.10.4.255"/> <!--Router B-->
  </AS>

  <AS id="60333">
    <Router interAddr="172.13.1.255"/> <!--Router C1-->
    <Router interAddr="172.13.2.255"/> <!--Router C2-->
    <Router interAddr="172.13.3.255"/> <!--Router C3-->
    <Router interAddr="172.13.4.255"/> <!--Router C4-->
    <DenyRouteOUT Address="172.10.8.0" Netmask="255.255.255.0"/>
    <DenyASOUT> 60111 </DenyASOUT>
  </AS>

  <Session id="1">
    <Router exterAddr="10.10.10.1" > </Router> <!--Router A1-->
    <Router exterAddr="10.10.10.2" > </Router> <!--Router C1-->
  </Session>

  <Session id="2">
    <Router exterAddr="10.10.20.1" > </Router> <!--Router A2-->
    <Router exterAddr="10.10.20.2" > </Router> <!--Router B-->
  </Session>

  <Session id="3">
    <Router exterAddr="10.10.30.1" > </Router> <!--Router B-->
    <Router exterAddr="10.10.30.2" > </Router> <!--Router C2-->
  </Session>
</BGPConfig>
```

Inside <AS> elements various rules can be sepecified:

- DenyRoute: deny route in IN and OUT traffic (Address and Netmask attributes must be specified.)
- DenyRouteIN : deny route in IN traffic (Address and Netmask attributes must be specified.)
- DenyRouteOUT: deny route in OUT traffic (Address and Netmask attributes must be specified.)
- DenyAS: deny routes learned by AS in IN and OUT traffic (AS id must be specified as the body of the element.)
- DenyASIN : deny routes learned by AS in IN traffic (AS id must be specified as the body of the element.)
- DenyASOUT: deny routes learned by AS in OUT traffic (AS id must be specified as the body of the element.)

CHAPTER

THIRTEEN

AD HOC ROUTING

13.1 Overview

In ad hoc networks, nodes are not familiar with the topology of their networks. Instead, they have to discover it: typically, a new node announces its presence and listens for announcements broadcast by its neighbors. Each node learns about others nearby and how to reach them, and may announce that it too can reach them. The difficulty of routing may be compounded by the fact that nodes may be mobile, which results in a changing topology.

Ad hoc routing protocols fall in two broad categories: proactive and reactive. *Proactive* or *table-driven* protocols maintain fresh lists of destinations and their routes by periodically distributing routing tables throughout the network. *Reactive* or *on-demand* protocols find a route on demand by flooding the network with Route Request packets.

The INET Framework contains the implementation of several ad hoc routing protocols including AODV, DSDV, DYMO and GPSR.

The easiest way to add routing to an ad hoc network is to use the ManetRouter NED type for nodes. ManetRouter contains a submodule named `routing` whose type is a parameter, so it can be configured to be an AODV router, a DYMO router, or a router of any other supported routing protocol. For example, you can configure ManetRouter nodes in the network to use AODV with the following ini file line:

```
**.routingApp.typename = "Aodv" # as an application
**.routing.typename = "Gpsr" # as a routing protocol module
```

There are also NED types called AodvRouter, DymoRouter, DsdvRouter, GpsrRouter, which are all ManetRouter's with the routing protocol submodule type set appropriately.

13.2 AODV

AODV (Ad hoc On-Demand Distance Vector Routing) is a routing protocol for mobile ad hoc networks and other wireless ad hoc networks. It offers quick adaptation to dynamic link conditions, low processing and memory overhead, low network utilization, and determines unicast routes to destinations within the ad hoc network.

The Aodv module type implements AODV, based on RFC 3561.

AodvRouter is a ManetRouter with the routing module type set to Aodv.

13.3 DSDV

DSDV (Destination-Sequenced Distance-Vector Routing) is a table-driven routing scheme for ad hoc mobile networks based on the Bellman-Ford algorithm.

The Dsdv module type implements DSDV. It is currently a partial implementation.

DsdvRouter is a ManetRouter with the routing module type set to Dsdv.

13.4 DYMO

The DYMO (Dynamic MANET On-demand) routing protocol is successor to the AODV routing protocol. DYMO can work as both a pro-active and as a reactive routing protocol, i.e. routes can be discovered just when they are needed.

The Dymo module type implements DYMO, based on the IETF draft *draft-ietf-manet-dymo-24*.

DymoRouter is a ManetRouter with the routing module type set to Dymo.

13.5 GPSR

GPSR (Greedy Perimeter Stateless Routing) is a routing protocol for mobile wireless networks that uses the geographic positions of nodes to make packet forwarding decisions.

The Gpsr module type implements GPSR, based on the paper "GPSR: Greedy Perimeter Stateless Routing for Wireless Networks" by Brad Karp and H. T. Kung, 2000. The implementation supports both GG and RNG planarization algorithms.

GpsrRouter is a ManetRouter with the routing module type set to Gpsr.

CHAPTER

FOURTEEN

QUEUEING MODEL

14.1 Overview

The INET queueing model provides reusable modules for various application areas. These modules can be used to build application traffic generators, queueing models for MAC protocols, traffic conditioning models for quality of service implementations, and so on.

14.1.1 Usage

The queueing modules can be used in two very different ways. For one, they can be connected to other INET modules using gates. In this case, the modules send and receive packets asynchronously as many other INET modules do. For example, application packet source and packet sink modules are used this way. The other way to use them is to directly call their C++ methods through one of the C++ interfaces of the contract package. In this case, the queueing modules are not connected to other INET modules at all. For example, MAC protocol modules use packet queues as submodules through C++ method calls.

14.1.2 Model

Most queueing model elements provide simple behaviors, so they are implemented as simple modules. But queueing elements can also be composed to form more complex behaviors. For example, priority queues, request-response based traffic generators, traffic shapers are usually implemented as compound modules. In fact, some of the queueing model elements provided by INET are actually realized as compound modules using composition.

The queueing model can be found in the `inet.queueing` NED package. All queueing model elements implement one or more NED module interfaces and also the corresponding C++ interfaces from the contract folder. As a minimum, they all implement the `IPacketQueueingElement` C++ interface.

14.1.3 Operation

Internally, connected queueing model elements most often communicate with each other using synchronous C++ method calls without utilizing `handleMessage()`. The only exception is when an operation takes a non-zero simulation time, such as when the processing of a packet is delayed. The connections between the model elements are simply used to designate the caller and the callee. Other modules can still send and receive messages through the gates of queueing model elements, but only `Packet` instances are allowed.

There are two new important operations on queueing model elements defined in `IPassivePacketSource` and `IPassivePacketSink`. Packets can be *pushed* into gates and packets can be *popped* from gates. Both of these operations are synchronous, they either finish successfully or throw an exception. The main difference between pushing and popping is the subject of the activity. In the former case, when a packet is pushed, the activity is initiated by the source of the packet. In contrast, when a packet is popped, the activity is initiated by the sink of the packet. In both cases, the passive elements can be asked via separate methods to tell if they can be pushed or popped in their current state either with respect to a specific packet or any packet thereof.

Queueing model elements can be divided into two categories with respect to the operation on a given gate: *passive* and *active*. The passive model elements are pushed into and popped from by other connected modules. In contrast, the active model elements push into and pop from other connected modules as they see fit. They implement the `IActivePacketSource` and `IActivePacketSink` C++ interfaces.

The active queueing elements take into consideration the state of the connected passive elements. That is, they push or pop packets only when the passive end is able to consume or provide, respectively. The queueing model elements also validate the assembled structure during module initialization with respect to the active and passive behavior of the connected gates. That is, active output gates must be connected to passive input gates, and active input gates must be connected to passive output gates.

Pushing a packet into a gate (and similarly popping a packet from a gate) can have far reaching consequences by triggering a chain of operations potentially by passing through multiple connected elements. For example, pushing a packet into a classifier will immediately push the packet into one of the connected queueing elements, and will also potentially lead to additional operations on further connected elements. Similarly, popping a packet from a scheduler will immediately pop a packet from one of the connected queueing elements, and will also potentially lead to additional operations on further connected elements.

In general, the following equation about the number of packets holds true for all queueing model elements:

#created + #pushed - #popped - #removed - #dropped = #available + #delayed

14.2 Sources

These modules act as sources of packets. An active packet source pushes packets to its output. A passive packet source returns a packet when it is popped by other queueing model elements.

- ActivePacketSource: generic source that produces packets periodically
- PassivePacketSource: generic source that provides packets as requested
- BurstyPacketProducer: mixes two different sources to generate bursty traffic
- QueueFiller: produces packets to continuously fill a queue
- ResponseProducer: produces complex response traffic based on the incoming request type
- PcapFilePacketProducer: replays packets from a PCAP file

14.3 Sinks

These modules act as sinks of packets. An active packet sink pops packets from its input. A passive packet sink is pushed with packets by other queueing model elements.

- ActivePacketSink: generic sink that collects packets periodically
- PassivePacketSink: generic sink that consumes packets as they arrive
- RequestConsumer: processes incoming requests in order and initiates response traffic
- PcapFilePacketConsumer: writes packets to a PCAP file

14.4 Queues

These modules store packets and maintain an ordering among them. Queues do not delay packets, so if a queue is not empty, then a packet is always available. When a packet is pushed into the input of a queue, then the packet is either stored, or if the queue is overloaded, it is dropped. When a packet is popped from the output of a queue, then one of the stored packets is returned.

The following simpler equation about the number of packets always holds true for queues:

#pushed - #popped - #dropped - #removed = #queueLength = #available

- PacketQueue: generic queue that provides ordering and selective dropping; it can be parameterized with a *comparator* and a *dropper* function (such functions can be defined in C++)
- DropHeadQueue: drops packets at the head of the queue
- DropTailQueue: drops packets at the tail of the queue, the most commonly used queue
- PriorityQueue: contains several subqueues that share a buffer
- RedDropperQueue: combines random early detection with a queue
- CompoundPacketQueue: allows building complex queues by pure NED composition

14.5 Buffers

These modules deal with memory allocation of packets without considering the ordering among them. A packet buffer generally doesn't have gates, and packets are not pushed into or popped from it.

- PacketBuffer: generic buffer that provides shared storage between several queues; it can be parameterized with a *dropper* function (such functions can be defined in C++)
- PriorityBuffer: drops packets based on the queue priority

14.6 Filters

These modules filter for specific packets while dropping the rest. When a packet is pushed into the input of a packet filter, then the filter either pushes the packet to its output or it simply drops the packet. In contrast, when a packet is popped from the output of a packet filter, then it continuously pops and drops packets from its input until it finds one that matches the filter criteria.

- PacketFilter: generic packet filter; it can be parameterized with a *filter* function (such functions can be defined in C++)
- ContentBasedFilter: drops packets based on the data they contain
- OrdinalBasedDropper: drops packets based on their ordinal number
- RateLimiter: drops packets above the specified packetrate or datarate
- RedDropper: drops packets based on random early detection

14.7 Classifiers

These modules classify packets to one of their outputs. When a packet is pushed into the input of a packet classifier, then it immediately pushes the packet to one of its outputs.

- PacketClassifier: generic packet classifier; it can be parameterized with a *classifier* function (such functions can be defined in C++)
- PriorityClassifier: classifies packets to the first non-full output
- WrrClassifier: classifies packets in a weighted round-robin manner
- LabelClassifier: classifies packets based on the attached labels
- MarkovClassifier: classifies packets based on the state of a Markov process
- UserPriorityClassifier: classifies packets based on the attached `UserPriorityReq`
- ContentBasedClassifier: classifies packets based on the data they contain

14.8 Schedulers

These modules schedule packets from one of their inputs. When a packet is popped from the output of a packet scheduler, then it immediately pops a packet from one of its inputs and returns that packet.

- PacketScheduler: generic packet scheduler; it can be parameterized with a *packet scheduler* function (such functions can be defined in C++)
- PriorityScheduler: schedules packets from the first non-empty source
- WrrScheduler: schedules packets in a weighted round-robin manner
- LabelScheduler: schedules packets based on the attached labels
- MarkovScheduler: schedules packets based on the state of a Markov process
- ContentBasedScheduler: schedules packets based on the data they contain

14.9 Servers

These modules process packets in order one by one. A packet server actively pops packets from its input when it sees fit, and it also actively pushes packets into its output.

- PacketServer: serves packets according to the processing time based on packet length
- TokenBasedServer: serves packets when the required number of tokens are available (token generators are described later)

14.10 Markers

These modules attach some information to packets on an individual basis. Packets can be both pushed into the input and popped from the output of packet markers.

- PacketLabeler: generic marker which attaches labels to matching packets; it can be parameterized with an `IPacketFilterFunction`
- ContentBasedLabeler: attaches labels to packets based on the data they contain
- PacketTagger: attaches tags such as outgoing interface, hopLimit, VLAN, user priority to matching packets; it can be parameterized with an `IPacketFilterFunction`
- ContentBasedTagger: attaches tags to packets based on the data they contain

- RedMarker: random early detection marker

14.11 Meters

These modules measure some property of a stream of packets. Packets can be both pushed into the input and popped from the output of packet meters.

- RateMeter: measures the packetrate and datarate of the packet stream

14.12 Token generators

These modules generate tokens for other modules. A token generator generally doesn't have gates and packets are not pushed into or popped from it.

- TimeBasedTokenGenerator: generates tokens based on elapsed simulation time
- PacketBasedTokenGenerator: generates tokens based on received packets
- SignalBasedTokenGenerator: generates tokens based on received signals
- QueueBasedTokenGenerator: generates tokens based on the state of a queue

14.13 Conditioners

These modules actively shape traffic by changing the order of packets, dropping packets, delaying packets, etc. Note that the capabilities of conditioners also includes delaying, which queues are not capable of. Traffic conditioners are generally built by composition using other queueing model elements.

- LeakyBucket: generic shaper with overflow and configurable output rate
- TokenBucket: generic shaper with overflow and configurable burstiness and output rate

14.14 Other queueing elements

There are also some other generic queueing model elements which don't fit well into any of the above categories.

- PacketGate: allows or prevents packets to pass through, either pushed or popped
- PacketMultiplexer: passively connects multiple inputs to a single output, packets are pushed into the inputs
- PacketDemultiplexer: passively connects a single input to multiple outputs, packets are popped from the outputs
- PacketDelayer: sends received packets to the output with some delay independently
- PacketCloner: sends one copy of each received packet to all outputs
- PacketHistory: keeps track of the last N packets which can be inspected in Qtenv
- PacketDuplicator: sends copies of each received packet to the only output
- OrdinalBasedDuplicator: duplicates received packets based on their ordinal number

CHAPTER

FIFTEEN

DIFFERENTIATED SERVICES

15.1 Overview

In the early days of the Internet, only best effort service was defined. The Internet delivers individually each packet, and delivery time is not guaranteed, moreover packets may even be dropped due to congestion at the routers of the network. It was assumed that transport protocols, and applications can overcome these deficiencies. This worked until FTP and email was the main applications of the Internet, but the newer applications such as Internet telephony and video conferencing cannot tolerate delay jitter and loss of data.

The first attempt to add QoS capabilities to the IP routing was Integrated Services. Integrated services provide resource assurance through resource reservation for individual application flows. An application flow is identified by the source and destination addresses and ports and the protocol id. Before data packets are sent the necessary resources must be allocated along the path from the source to the destination. At the hops from the source to the destination each router must examine the packets, and decide if it belongs to a reserved application flow. This could cause a memory and processing demand in the routers. Other drawback is that the reservation must be periodically refreshed, so there is an overhead during the data transmission too.

Differentiated Services is a more scalable approach to offer a better than best-effort service. Differentiated Services do not require resource reservation setup. Instead of making per-flow reservations, Differentiated Services divides the traffic into a small number of *forwarding classes*. The forwarding class is directly encoded into the packet header. After packets are marked with their forwarding classes at the edge of the network, the interior nodes of the network can use this information to differentiate the treatment of packets. The forwarding classes may indicate drop priority and resource priority. For example, when a link is congested, the network will drop packets with the highest drop priority first.

In the Differentiated Service architecture, the network is partitioned into DiffServ domains. Within each domain the resources of the domain are allocated to forwarding classes, taking into account the available resources and the traffic flows. There are *service level agreements* (SLA) between the users and service providers, and between the domains that describe the mapping of packets to forwarding classes and the allowed traffic profile for each class. The routers at the edge of the network are responsible for marking the packets and protect the domain from misbehaving traffic sources. Nonconforming traffic may be dropped, delayed, or marked with a different forwarding class.

15.1.1 Implemented Standards

The implementation follows these RFCs below:

- RFC 2474: Definition of the Differentiated Services Field (DS Field) in the IPv4 and IPv6 Headers
- RFC 2475: An Architecture for Differentiated Services
- RFC 2597: Assured Forwarding PHB Group
- RFC 2697: A Single Rate Three Color Marker
- RFC 2698: A Two Rate Three Color Marker
- RFC 3246: An Expedited Forwarding PHB (Per-Hop Behavior)

- RFC 3290: An Informal Management Model for Diffserv Routers

15.2 Architecture of NICs

Network interface modules, such as PppInterface and EthernetInterface, may contain traffic conditioners in their input and output data path.

Network interfaces may also contain an optional external queue component. In the absence of an external queue module, Ppp and EtherMac use an internal drop-tail queue to buffer the packets while the line is busy.

15.2.1 Traffic Conditioners

Traffic conditioners have one input and one output gate as defined in the ITrafficConditioner interface. They can transform the incoming traffic by dropping or delaying packets. They can also set the DSCP field of the packet, or mark them other way, for differentiated handling in the queues.

Traffic conditioners perform the following actions:

- classify the incoming packets
- meter the traffic in each class
- marks/drops packets depending on the result of metering
- shape the traffic by delaying packets to conform to the desired traffic profile

INET provides classifier, meter, and marker modules, that can be composed to build a traffic conditioner as a compound module.

15.2.2 Output Queues

Queue components must implement the IPacketQueue module interface. In addition to having one input and one output gate, these components must implement a passive queue behaviour: they only deliver a packet when the module connected to their output explicitly requests it. (In C++ terms, the module must implement the `IPacketQueue` interface. The next module requests a packet by calling the `requestPacket()` method of that interface.)

15.3 Simple modules

This section describes the primitive elements from which traffic conditioners and output queues can be built. The next sections shows some examples, how these queues, schedulers, droppers, classifiers, meters, markers can be combined.

The type of the components are:

- `queue`: container of packets, accessed as FIFO
- `dropper`: attached to one or more queue, it can limit the queue length below some threshold by selectively dropping packets
- `scheduler`: decide which packet is transmitted first, when more packets are available on their inputs
- `classifier`: classify the received packets according to their content (e.g. source/destination, address and port, protocol, dscp field of IP datagrams) and forward them to the corresponding output gate.
- `meter`: classify the received packets according to the temporal characteristic of their traffic stream
- `marker`: marks packets by setting their fields to control their further processing

15.3.1 Queues

When packets arrive at higher rate, than the interface can trasmit, they are getting queued.

Queue elements store packets until they can be transmitted. They have one input and one output gate. Queues may have one or more thresholds associated with them.

Received packets are enqueued and stored until the module connected to their output asks a packet by calling the `requestPacket()` method.

They should be able to notify the module connected to its output about the arrival of new packets.

FIFO Queue

The FifoQueue module implements a passive FIFO queue with unlimited buffer space. It can be combined with algorithmic droppers and schedulers to form an IPacketQueue compound module.

The C++ class implements the `IQueueAccess` and `IPacketQueue` interfaces.

DropTailQueue

The other primitive queue module is DropTailQueue. Its capacity can be specified by the `packetCapacity` parameter. When the number of stored packet reached the capacity of the queue, further packets are dropped. Because this module contains a built-in dropping strategy, it cannot be combined with algorithmic droppers as FifoQueue can be. However its output can be connected to schedulers.

This module implements the IPacketQueue interface, so it can be used as the queue component of interface card per se.

15.3.2 Droppers

Algorithmic droppers selectively drop received packets based on some condition. The condition can be either deterministic (e.g. to bound the queue length), or probabilistic (e.g. RED queues).

Other kind of droppers are absolute droppers; they drop each received packet. They can be used to discard excess traffic, i.e. packets whose arrival rate exceeds the allowed maximum. In INET the Sink module can be used as an absolute dropper.

The algorithmic droppers in INET are ThresholdDropper and RedDropper. These modules has multiple input and multiple output gates. Packets that arrive on gate `in[i]` are forwarded to gate `out[i]` (unless they are dropped). However the queues attached to the output gates are viewed as a whole, i.e. the queue length parameter of the dropping algorithm is the sum of the individual queue lengths. This way we can emulate shared buffers of the queues. Note, that it is also possible to connect each output to the same queue module.

Threshold Dropper

The ThresholdDropper module selectively drops packets, based on the available buffer space of the queues attached to its output. The buffer space can be specified as the count of packets, or as the size in bytes.

The module sums the buffer lengths of its outputs and if enqueuing a packet would exceed the configured capacities, then the packet will be dropped instead.

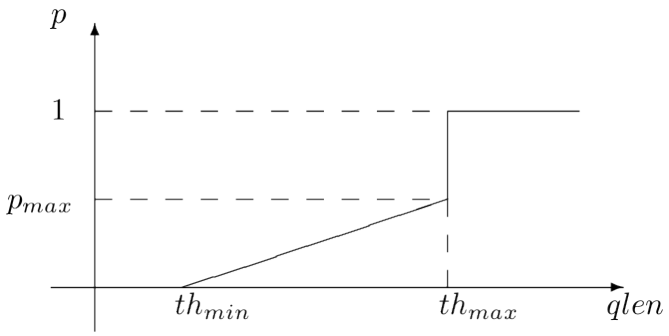
By attaching a ThresholdDropper to the input of a FIFO queue, you can compose a drop tail queue. Shared buffer space can be modeled by attaching more FIFO queues to the output.

RED Dropper

The RedDropper module implements Random Early Detection ([**?**]).

It has n input and n output gates (specified by the `numGates` parameter). Packets that arrive at the i^{th} input gate are forwarded to the i^{th} output gate, or dropped. The output gates must be connected to simple modules implementing the `IQueueAccess` C++ interface (e.g. FifoQueue).

The module sums the used buffer space of the queues attached to the output gates. If it is below a minimum threshold, the packet won't be dropped, if above a maximum threshold, it will be dropped, if it is between the minimum and maximum threshold, it will be dropped by a given probability. This probability determined by a linear function which is 0 at the minth and maxp at maxth.



The queue length can be smoothed by specifying the `wq` parameter. The average queue length used in the tests are computed by the formula:

$$avg = (1 - wq) * avg + wq * qlen$$

The `minth`, `maxth`, and `maxp` parameters can be specified separately for each input gate, so this module can be used to implement different packet drop priorities.

15.3.3 Schedulers

Scheduler modules decide which queue can send a packet, when the interface is ready to transmit one. They have several input gates and one output gate.

Modules that are connected to the inputs of a scheduler must implement the `IPacketQueue` C++ interface. Schedulers also implement `IPacketQueue`, so they can be cascaded to other schedulers, and can be used as the output module of IPacketQueue's.

There are several possible scheduling discipline (first come/first served, priority, weighted fair, weighted round-robin, deadline-based, rate-based). INET contains implementation of priority and weighted round-robin schedulers.

Priority Scheduler

The PriorityScheduler module implements a strict priority scheduler. Packets that arrived on `in[0]` has the highest priority, then packets arrived on `in[1]`, and so on. If more packets available when one is requested, then the one with highest priority is chosen. Packets with lower priority are transmitted only when there are no packets on the inputs with higher priorities.

PriorityScheduler must be used with care, because a large volume of higher packets can starve lower priority packets. Therefore it is necessary to limit the rate of higher priority packets to a fraction of the output datarate.

PriorityScheduler can be used to implement the `EF` PHB.

Weighted Round Robin Scheduler

The WrrScheduler module implements a weighted round-robin scheduler. The scheduler visits the input gates in turn and selects the number of packets for transmission based on their weight.

For example if the module has three input gates, and the weights are 3, 2, and 1, then packets are transmitted in this order:

```
A, A, A, B, B, C, A, A, A, B, B, C, ...
```

where A packets arrived on `in[0]`, B packets on `in[1]`, and C packets on `in[2]`. If there are no packets in the current one when a packet is requested, then the next one is chosen that has enough tokens.

If the size of the packets are equal, then WrrScheduler divides the available bandwith according to the weights. In each case, it allocates the bandwith fairly. Each flow receives a guaranteed minimum bandwith, which is ensured even if other flows exceed their share (flow isolation). It is also efficiently uses the channel, because if some traffic is smaller than its share of bandwidth, then the rest is allocated to the other flows.

WrrScheduler can be used to implement the `AFxy` PHBs.

15.3.4 Classifiers

Classifier modules have one input and many output gates. They examine the received packets, and forward them to the appropriate output gate based on the content of some portion of the packet header. You can read more about classifiers in RFC 2475 and RFC 3290.

The `inet.networklayer.diffserv` package contains two classifiers: MultiFieldClassifier to classify the packets at the edge routers of the DiffServ domain, and BehaviorAggregateClassifier to classify the packets at the core routers.

Multi-field Classifier

The MultiFieldClassifier module can be used to identify micro-flows in the incoming traffic. The flow is identified by the source and destination addresses, the protocol id, and the source and destination ports of the IP packet.

The classifier can be configured by specifying a list of filters. Each filter can specify a source/destination address mask, protocol, source/destination port range, and bits of TypeOfService/TrafficClass field to be matched. They also specify the index of the output gate matching packet should be forwarded to. The first matching filter determines the output gate, if there are no matching filters, then `defaultOut` is chosen.

The configuration of the module is given as an XML document. The document element must contain a list of `<filter>` elements. The filter element has a mandatory `@gate` attribute that gives the index of the gate for packets matching the filter. Other attributes are optional and specify the condition of matching:

- `@srcAddress`, `@srcPrefixLength`: to match the source address of the IP
- `@destAddress`, `@destPrefixLength`:
- `@protocol`: matches the protocol field of the IP packet. Its value can be a name (e.g. "udp", "tcp"), or the numeric code of the protocol.
- `@tos`,@tosMask: matches bits of the TypeOfService/TrafficClass field of the IP packet.
- `@srcPort`: matches the source port of the TCP or UDP packet.
- `@srcPortMin`, `@srcPortMax`: matches a range of source ports.
- `@destPort`: matches the destination port of the TCP or UDP packet.
- `@destPortMin`, `@destPortMax`: matches a range of destination ports.

The following example configuration specifies

- to transmit packets received from the 192.168.1.x subnet on gate 0,

- to transmit packets addressed to port 5060 on gate 1,
- to transmit packets having CS7 in their DSCP field on gate 2,
- to transmit other packets on `defaultGate`.

```
<filters>
  <filter srcAddress="192.168.1.0" srcPrefixLength="24" gate="0"/>
  <filter protocol="udp" destPort="5060" gate="1"/>
  <filter tos="0b00111000" tosMask="0x3f" gate="2"/>
</filters>
```

Behavior Aggregate Classifier

The BehaviorAggregateClassifier module can be used to read the DSCP field from the IP datagram, and direct the packet to the corresponding output gate. The DSCP value is the lower six bits of the TypeOfService/TrafficClass field. Core routers usually use this classifier to guide the packet to the appropriate queue.

DSCP values are enumerated in the `dscps` parameter. The first value is for gate `out[0]`, the second for `out[1]`, so on. If the received packet has a DSCP value not enumerated in the `dscps` parameter, it will be forwarded to the `defaultOut` gate.

15.3.5 Meters

Meters classify the packets based on the temporal characteristics of their arrival. The arrival rate of packets is compared to an allowed traffic profile, and packets are decided to be green (in-profile) or red (out-of-profile). Some meters apply more than two conformance level, e.g. in three color meters the partially conforming packets are classified as yellow.

The allowed traffic profile is usually specified by a token bucket. In this model, a bucket is filled in with tokens with a specified rate, until it reaches its maximum capacity. When a packet arrives, the bucket is examined. If it contains at least as many tokens as the length of the packet, then that tokens are removed, and the packet marked as conforming to the traffic profile. If the bucket contains less tokens than needed, it left unchanged, but the packet marked as non-conforming.

Meters has two modes: color-blind and color-aware. In color-blind mode, the color assigned by a previous meter does not affect the classification of the packet in subsequent meters. In color-aware mode, the color of the packet can not be changed to a less conforming color: if a packet is classified as non-conforming by a meter, it also handled as non-conforming in later meters in the data path.

Important: Meters take into account the length of the IP packet only, L2 headers are omitted from the length calculation. If they receive a packet which is not an IP datagram and does not encapsulate an IP datagram, an error occurs.

TokenBucketMeter

The TokenBucketMeter module implements a simple token bucket meter. The module has two output, one for green packets, and one for red packets. When a packet arrives, the gained tokens are added to the bucket, and the number of tokens equal to the size of the packet are subtracted.

Packets are classified according to two parameters, Committed Information Rate (cir), Committed Burst Size (cbs), to be either green, or red.

Green traffic is guaranteed to be under $cir * (t_1 - t_0) + 8 * cbs$ in every $[t_0, t_1]$ interval.

SingleRateThreeColorMeter

The SingleRateThreeColorMeter module implements a Single Rate Three Color Meter (RFC 2697). The module has three output for green, yellow, and red packets.

Packets are classified according to three parameters, Committed Information Rate (cir), Committed Burst Size (cbs), and Excess Burst Size (ebs), to be either green, yellow or red. The green traffic is guaranteed to be under $cir * (t_1 - t_0) + 8 * cbs$, while the green+yellow traffic to be under $cir * (t_1 - t_0) + 8 * (cbs + ebs)$ in every $[t_0, t_1]$ interval.

TwoRateThreeColorMeter

The TwoRateThreeColorMeter module implements a Two Rate Three Color Meter (RFC 2698). The module has three output gates for the green, yellow, and red packets.

It classifies the packets based on two rates, Peak Information Rate (pir) and Committed Information Rate (cir), and their associated burst sizes (pbs and cbs) to be either green, yellow or red. The green traffic is under $pir * (t_1 - t_0) + 8 * pbs$ and $cir * (t_1 - t_0) + 8 * cbs$, the yellow traffic is under $pir * (t_1 - t_0) + 8 * pbs$ in every $[t_0, t_1]$ interval.

15.3.6 Markers

DSCP markers sets the codepoint of the crossing packets. The codepoint determines the further processing of the packet in the router or in the core of the DiffServ domain.

The DscpMarker module sets the DSCP field (lower six bit of TypeOfService/TrafficClass) of IP datagrams to the value specified by the `dscps` parameter. The `dscps` parameter is a space separated list of codepoints. You can specify a different value for each input gate; packets arrived at the i^{th} input gate are marked with the i^{th} value. If there are fewer values, than gates, then the last one is used for extra gates.

The DSCP values are enumerated in the `DSCP.msg` file. You can use both names and integer values in the `dscps` parameter.

For example the following lines are equivalent:

```
**.dscps = "EF 0x0a 0b00001000"
**.dscps = "46 AF11 8"
```

15.4 Compound modules

15.4.1 AFxyQueue

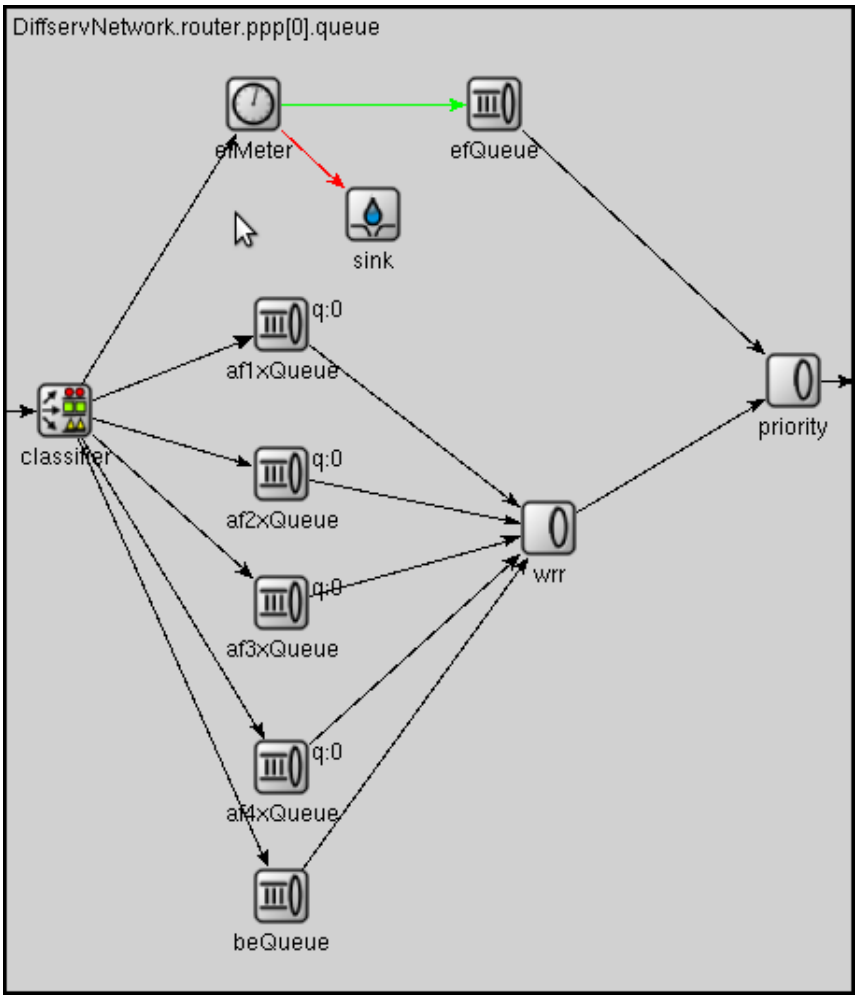
The AFxyQueue module is an example queue, that implements one class of the Assured Forwarding PHB group (RFC 2597).

Packets with the same AFx class, but different drop priorities arrive at the `afx1In`, `afx2In`, and `afx3In` gates. The received packets are stored in the same queue. Before the packet is enqueued, a RED dropping algorithm may decide to selectively drop them, based on the average length of the queue and the RED parameters of the drop priority of the packet.

The afxyMinth, afxyMaxth, and afxyMaxp parameters must have values that ensure that packets with lower drop priorities are dropped with lower or equal probability than packets with higher drop priorities.

15.4.2 DiffservQeueue

The DiffservQueue is an example queue, that can be used in interfaces of DS core and edge nodes to support the AFxy (RFC 2597) and EF (RFC 3246) PHB's.



The incoming packets are first classified according to their DSCP field. DSCP's other than AFxy and EF are handled as BE (best effort).

EF packets are stored in a dedicated queue, and served first when a packet is requested. Because they can preempt the other queues, the rate of the EF packets should be limited to a fraction of the bandwith of the link. This is achieved by metering the EF traffic with a token bucket meter and dropping packets that does not conform to the traffic profile.

There are other queues for AFx classes and BE. The AFx queues use RED to implement 3 different drop priorities within the class. BE packets are stored in a drop tail queue. Packets from AFxy and BE queues are sheduled by a WRR scheduler, which ensures that the remaining bandwith is allocated among the classes according to the specified weights.

CHAPTER

SIXTEEN

THE MPLS MODELS

16.1 Overview

Multi-Protocol Label Switching (MPLS) is a "layer 2.5" protocol for high-performance telecommunications networks. MPLS directs data from one network node to the next based on numeric labels instead of network addresses, avoiding complex lookups in a routing table and allowing traffic engineering. The labels identify virtual links (label-switched paths or LSPs, also called MPLS tunnels) between distant nodes rather than endpoints. The routers that make up a label-switched network are called label-switching routers (LSRs) inside the network ("transit nodes"), and label edge routers (LER) on the edges of the network ("ingress" or "egress" nodes).

A fundamental MPLS concept is that two LSRs must agree on the meaning of the labels used to forward traffic between and through them. This common understanding is achieved by using signaling protocols by which one LSR informs another of label bindings it has made. Such signaling protocols are also called label distribution protocols. The two main label distribution protocols used with MPLS are LDP and RSVP-TE.

INET provides basic support for building MPLS simulations. It provides models for the MPLS, LDP and RSVP-TE protocols and their associated data structures, and preassembled MPLS-capable router models.

16.2 Core Modules

The core modules are:

- Mpls implements the MPLS protocol
- LibTable holds the LIB (Label Information Base)
- Ldp implements the LDP signaling protocol for MPLS
- RsvpTe implements the RSVP-TE signaling protocol for MPLS
- Ted contains the Traffic Engineering Database
- LinkStateRouting is a simple link-state routing protocol
- RsvpClassifier is a configurable ingress classifier for MPLS

16.2.1 Mpls

The Mpls module implements the MPLS protocol. MPLS is situated between layer 2 and 3, and its main function is to switch packets based on their labels. For that, it relies on the data structure called LIB (Label Information Base). LIB is fundamentally a table with the following columns: *input-interface*, *input-label*, *output-interface*, *label-operation(s)*.

Upon receiving a labelled packet from another LSR, MPLS first extracts the incoming interface and incoming label pair, and then looks it up in local LIB. If a matching entry is found, it applies the prescribed label operations, and forwards the packet to the output interface.

Label operations can be the following:

- *Push* adds a new MPLS label to a packet. (A packet may contain multiple labels, acting as a stack.) When a normal IP packet enters an LSP, the new label will be the first label on the packet.
- *Pop* removes the topmost MPLS label from a packet. This is typically done at either the penultimate or the egress router.
- *Swap*: Replaces the topmost label with a new label.

In INET, the local LIB is stored in a LibTable module in the router.

Upon receiving an unlabelled (e.g. plain IPv4) packet, MPLS first determines the forwarding equivalence class (FEC) for the packet using an ingress classifier, and then inserts one or more labels in the packet's newly created MPLS header. The packet is then passed on to the next hop router for the LSP.

The ingress classifier is also a separate module; it is selected depending on the choice of the signaling protocol.

16.2.2 LibTable

LibTable stores the LIB (Label Information Base), as described in the previous section. LibTable is expected to have one instance in the router.

LIB is normally filled and maintained by label distribution protocols (RSVP-TE, LDP), but in INET it is possible to preload it with initial contents.

The LibTable module accepts an XML config file whose structure follows the contents of the LIB table. An example configuration:

```
<libtable>
    <libentry>
        <inLabel>203</inLabel>
        <inInterface>ppp1</inInterface>
        <outInterface>ppp2</outInterface>
        <outLabel>
            <op code="pop"/>
            <op code="swap" value="200"/>
            <op code="push" value="300"/>
        </outLabel>
        <color>200</color>
    </libentry>
</libtable>
```

There can be multiple `<libentry>` elements, each describing a row in the table. Colums are given as child elements: `<inLabel>`, `<inInterface>`, etc. The `<color>` element is optional, and it only exists to be able to color LSPs on the GUI. It is not used by the protocols.

16.2.3 Ldp

The Ldp module implements the Label Distribution Protocol (LDP). LDP is used to establish LSPs in an MPLS network when traffic engineering is not required. It establishes LSPs that follow the existing IP routing table, and is particularly well suited for establishing a full mesh of LSPs between all of the routers on the network.

LDP relies on the underlying routing information provided by a routing protocol in order to forward label packets. The router's forwarding information base, or FIB, is responsible for determining the hop-by-hop path through the network.

In INET, the Ldp module takes routing information from Ted module. The Ted instance in the network is filled and maintained by a LinkStateRouting module. Unfortunately, it is currently not possible to use other routing protocol implementations such as Ospfv2 in conjunction with Ldp.

When Ldp is used as signaling protocol, it also serves as ingress classifier for Mpls.

16.2.4 Ted

The Ted module contains the Traffic Engineering Database (TED). In INET, Ted contains a link state database, including reservations for each link by RSVP-TE.

16.2.5 LinkStateRouting

The LinkStateRouting module provides a simple link state routing protocol. It uses Ted as its link state database. Unfortunately, the LinkStateRouting module cannot operate independently, it can only be used inside an MPLS router.

16.2.6 RsvpTe

The RsvpTe module implements RSVP-TE (Resource Reservation Protocol – Traffic Engineering), as signaling protocol for MPLS. RSVP-TE handles bandwidth allocation and allows traffic engineering across an MPLS network. Like LDP, RSVP uses discovery messages and advertisements to exchange LSP path information between all hosts. However, whereas LDP is restricted to using the configured IGP's shortest path as the transit path through the network, RSVP can take taking into consideration network constraint parameters such as available bandwidth and explicit hops. RSVP uses a combination of the Constrained Shortest Path First (CSPF) algorithm and Explicit Route Objects (EROs) to determine how traffic is routed through the network.

When RsvpTe is used as signaling protocol, Mpls needs a separate ingress classifier module, which is usually a RsvpClassifier.

The RsvpTe module allows LSPs to be specified statically in an XML config file. An example `traffic.xml` file:

```
<sessions>
    <session>
        <endpoint>host3</endpoint>
        <tunnel_id>1</tunnel_id>
        <paths>
            <path>
                <lspid>100</lspid>
                <bandwidth>100000</bandwidth>
                <route>
                    <node>10.1.1.1</node>
                    <lnode>10.1.2.1</lnode>
                    <node>10.1.4.1</node>
                    <node>10.1.5.1</node>
                </route>
                <permanent>true</permanent>
                <color>100</color>
            </path>
        </paths>
    </session>
</sessions>
```

In the route, `<node>` stands for strict hop, and `<lnode>` for loose hop.

Paths can also be set up and torn down dynamically with ScenarioManager commands (see chapter *Scenario Scripting*). RsvpTe understands the `<add-session>` and `<del-session>` ScenarioManager commands. The contents of the `<add-session>` element can be the same as the `<session>` element for the `traffic.xml` above. The `<del-command>` element syntax is also similar, but only `<endpoint>`, `<tunnel_id>` and `<lspid>` need to be specified.

The following is an example `scenario.xml` file:

```
<scenario>
    <at t="2">
        <add-session module="LSR1.rsvp">
            <endpoint>10.2.1.1</endpoint>
            <tunnel_id>1</tunnel_id>
            <paths>
                ...
            </paths>
        </add-session>
    </at>
    <at t="2.4">
        <del-session module="LSR1.rsvp">
            <endpoint>10.2.1.1</endpoint>
            <tunnel_id>1</tunnel_id>
            <paths>
                <path>
                    <lspid>100</lspid>
                </path>
            </paths>
        </del-session>
    </at>
</scenario>
```

16.3 Classifier

The RsvpClassifier module implements an ingress classifier for Mpls when using RsvpTe for signaling. The classifier can be configured with an XML config file.

```
**.classifier.config = xmldoc("fectable.xml");
```

An example `fectable.xml` file:

```
<fectable>
    <fecentry>
        <id>1</id>
        <destination>host5</destination>
        <source>host1</source>
        <tunnel_id>1</tunnel_id>
        <lspid>100</lspid>
    </fecentry>
</fectable>
```

16.4 MPLS-Enabled Router Models

INET provides the following pre-assembled MPLS routers:

- LdpMplsRouter is an MPLS router with the LDP signaling protocol
- RsvpMplsRouter is an MPLS router with the RSVP-TE signaling protocol

CHAPTER

SEVENTEEN

POINT-TO-POINT LINKS

17.1 Overview

For simulating wired point-to-point links, the INET Framework contains a minimal implementation of the PPP protocol and a corresponding network interface module.

- Ppp is a simple module that performs encapsulation of network datagrams into PPP frames and decapsulation of the incoming PPP frames. It can be connected to the network layer directly or can be configured to get the outgoing messages from an output queue. The module collects statistics about the transmitted and dropped packages.
- PppInterface is a compound module that complements the Ppp module with an output queue. It implements the IWiredInterface interface. Input and output hooks can be configured for further processing of the network messages.

PPP (RFC 1661) is a complex protocol which, in addition to providing a method for encapsulating multi-protocol datagrams, also contains control protocols for establishing, configuring, and testing the data-link connection (LCP) and for configuring different network-layer protocols (NCP).

The INET implementation only covers encapsulation and decapsulation of data into PPP frames. Control protocols, which do not have a significant effect on the links' capacity and latency during normal link operation, are not simulated. In addition, header field compressions (PFC and ACFC) are also bot supported, so a simulated PPP frame always contains 1-byte Address and Control fields and a 2-byte Protocol field.

17.2 The PPP module

The PPP module receives packets from the upper layer in the `netwIn` gate, adds a PppHeader, and send it to the physical layer through the `phys` gate. The packet with PppHeader is received from the `phys` and sent to the upper layer immediately through the `netwOut` gate.

Incoming datagrams are waiting in a queue if the line is currently busy. In routers, PPP relies on an external queue module (implementing IPacketQueue) to model finite buffer, implement QoS and/or RED, and requests packets from this external queue one-by-one. The name of this queue is given as the `queueModule` parameter.

In hosts, no such queue is used, so Ppp contains an internal queue to store packets wainting for transmission. Conceptually the queue is of inifinite size, but for better diagnostics one can specify a hard limit in the `packetCapacity` parameter – if this is exceeded, the simulation stops with an error.

The module can be used in simulations where the nodes are connected and disconnected dinamically. If the channel between the PPP modules is down, the messages received from the upper layer are dropped (including the messages waiting in the queue). When the connection is restored it will poll the queue and transmits the messages again.

The PPP module registers itself in the interface table of the node. The `mtu` of the entry can be specified by the `mtu` module parameter. The module checks the state of the physical link and updates the entry in the interface table.

17.3 PppInterface

PppInterface is a compound module that implements the IWiredInterface interface. It contains a Ppp module and a passive queue for the messages received from the network layer.

The queue type is specified by the `typename` parameter of the queue submodule. It can be set to `PacketQueue` or to a module type implementing the IPacketQueue interface. There are implementations with QoS and RED support.

In typical use of the Ppp module it is augmented with other nodes that monitor the traffic or simulate package loss and duplication. The PppInterface module abstract that usage by adding IHook components to the network input and output of the Ppp component. Any number of hook can be added by specifying the `numOutputHooks` and `numInputHooks` parameters and the types of the `outputHook` and `inputHook` components. The hooks are chained in their numeric order.

CHAPTER

EIGHTEEN

THE ETHERNET MODEL

18.1 Overview

Ethernet is the most popular wired LAN technology nowadays, and its use is also growing in metropolitan area and wide area networks. Since its introduction in 1980, Ethernet data transfer rates have increased from the original 10Mb/s to the latest 400Gb/s. Originally, The technology has changed from using coaxial cables and repeaters to using unshielded twisted-pair cables with hubs and switches. Today, switched Ethernet is prevalent, and most links operate in full duplex mode. The INET Framework contains support for all major Ethernet technologies and device types.

In Ethernet networks containing multiple switches, broadcast storms are prevented by use of a spanning tree protocol (STP, RSTP) that disables selected links to eliminate cycles from the topology. Ethernet switch models in INET contain support for STP and RSTP.

18.2 Nodes

There are several node models that can be used in an Ethernet network:

- Node models such as StandardHost and Router are Ethernet-capable
- EtherSwitch models an Ethernet switch, i.e. a multiport bridging device
- EtherHub models an Ethernet hub or multiport repeater
- EtherBus models the coaxial cable (10BASE2 or 10BASE5 network segments) on legacy Ethernet networks
- EtherHost is a sample node which can be used to generate "raw" Ethernet traffic

18.2.1 EtherSwitch

EtherSwitch models an Ethernet switch. Ethernet switches play an important role in modern Ethernet LANs. Unlike passive hubs and repeaters that work in the physical layer, the switches operate in the data link layer and relay frames between the connected subnets.

In modern Ethernet LANs, each node is connected to the switch directly by full duplex lines, so no collisions are possible. In this case, the CSMA/CD is not needed and the channel utilization can be high.

The `duplexMode` parameters of the MACs must be set according to the medium connected to the port; if collisions are possible (it's a bus or hub) it must be set to false, otherwise it can be set to true. By default it uses half-duplex MAC with CSMA/CD.

18.2.2 EtherHub

EtherHub models an Ethernet hub. Ethernet hubs are a simple broadcast devices. Messages arriving on a port are regenerated and broadcast to every other port.

The connections connected to the hub must have the same data rate. Cable lengths should be reflected in the delays of the connections.

18.2.3 EtherBus

The EtherBus component can model a common coaxial cable found in early Ethernet LANs. The nodes are attached via taps at specific positions on the cable. When a node sends a signal, it will propagate along the cable in both directions at the given propagation speed.

The gates of the EtherBus represent taps. The positions of the taps are given by the `positions` parameter as a space separated list of distances in metres. If there are more gates then positions given, the last distance is repeated. The bus component send the incoming message in one direction and a copy of the message to the other direction (except at the ends). The propagation delays are computed from the distances of the taps and the `propagationSpeed` parameter.

18.3 The Physical Layer

Stations on an Ethernet networks are connected by coaxial, twisted pair or fibre cables. (Coaxial only has historical importance, but is supported by INET anyway.) There are several cable types specified in the standard.

In the INET framework, the cables are represented by connections. The connections used in Ethernet LANs must be derived from ned::`DatarateChannel` and should have their `delay` and `datarate` parameters set. The delay parameter can be used to model the distance between the nodes. The datarate parameter can have four values:

- 10Mbps (classic Ethernet)
- 100Mbps (Fast Ethernet)
- 1Gbps (Gigabit Ethernet, GbE)
- 10Gbps (10 Gigabit Ethernet, 10GbE)
- 40Gbps (40 Gigabit Ethernet, 40GbE)
- 100Gbps (100 Gigabit Ethernet, 100GbE)

There is currently no support for 200Gbps and 400Gbps Ethernet.

Eth10M, Eth100M, Eth1G, Eth10G, Eth40G, Eth100G

18.4 Ethernet Interface

The EthernetInterface compound module implements the IWiredInterface interface. Complements EtherMac and EtherEncap with an output queue for QoS and RED support. It also has configurable input/output filters as IHook components similarly to the PppInterface module.

The Ethernet MAC (Media Access Control) layer transmits the Ethernet frames on the physical media. This is a sublayer within the data link layer. Because encapsulation/decapsulation is not always needed (e.g. switches does not do encapsulation/decapsulation), it is implemented in a separate modules (e.g. EtherEncap) that are part of the LLC layer.

Nowadays almost all Ethernet networks operate using full-duplex point-to-point connections between hosts and switches. This means that there are no collisions, and the behaviour of the MAC component is much simpler than in classic Ethernet that used coaxial cables and hubs. The INET framework contains two MAC modules for

Ethernet: the EtherMacFullDuplex is simpler to understand and easier to extend, because it supports only full-duplex connections. The EtherMac module implements the full MAC functionality including CSMA/CD, it can operate both half-duplex and full-duplex mode.

18.5 Components

The following components are present in the model:

- EtherMacFullDuplex
- EtherMac
- EtherEncap
- MacRelayUnit
- MacAddressTable
- Ieee8021dRelay

18.5.1 EtherMacFullDuplex

From the two MAC implementation EtherMacFullDuplex is the simpler one, it operates only in full-duplex mode (its `duplexEnabled` parameter fixed to `true` in its NED definition). This module does not need to implement CSMA/CD, so there is no collision detection, retransmission with exponential backoff, carrier extension and frame bursting.

18.5.2 EtherMac

Ethernet MAC layer implementing CSMA/CD. It supports both half-duplex and full-duplex operations; in full-duplex mode it behaves as EtherMacFullDuplex. In half-duplex mode it detects collisions, sends jam messages and retransmit frames upon collisions using the exponential backoff algorithm. In Gigabit Ethernet networks it supports carrier extension and frame bursting. Carrier extension can be turned off by setting the `carrierExtension` parameter to `false`.

18.5.3 EtherEncap

The EtherEncap module performs Ethernet II or Ethernet with SNAP encapsulation/decapsulation.

18.5.4 MacRelayUnit

INET framework ethernet switches are built from IMacRelayUnit components. Each relay unit has N input and output gates for sending/receiving Ethernet frames. They should be connected to EthernetInterface modules.

The relay unit holds a table for the destination address -> output port mapping in a MacAddressTable module. When the relay unit receives a data frame, it updates the table with the source address->input port.

If the destination address is not found in the table, the frame is broadcast. The frame is not sent to the same port it was received from, because then the target should already have received the original frame.

A simple scheme for sending PAUSE frames is built in (although users will probably change it). When the buffer level goes above a high watermark, PAUSE frames are sent on all ports. The watermark and the pause time is configurable; use zero values to disable the PAUSE feature.

18.5.5 MacAddressTable

The MacAddressTable module stores the mapping between ports and MAC addresses. Entries are deleted if their age exceeds a certain limit.

If needed, address tables can be pre-loaded from text files at the beginning of the simulation; this controlled by the `addressTableFile` module parameter. In the file, each line contains a literal 0 (reserved for VLAN id), a hexadecimal MAC address and a decimal port number, separated by tabs. Comment lines beginning with '#' are also allowed:

```
0    01 ff ff ff ff    0
0    00-ff-ff-ee-d1    1
0    0A:AA:BC:DE:FF    2
```

Entries are deleted if their age exceeds the duration given as the `agingTime` parameter.

18.5.6 Ieee8021dRelay

Ieee8021dRelay is a MAC relay unit that should be used instead of MacRelayUnit that when STP or RSTP is needed.

18.5.7 Stp

The Stp module type implements Spanning Tree Protocol (STP). STP is a network protocol that builds a loop-free logical topology for Ethernet networks. The basic function of STP is to prevent bridge loops and the broadcast radiation that results from them.

STP creates a spanning tree within a network of connected layer-2 bridges, and disables those links that are not part of the spanning tree, leaving a single active path between any two network nodes.

18.5.8 Rstp

Rstp implements Rapid Spanning Tree Protocol (RSTP), an improved version of STP. RSTP provides significantly faster recovery in response to network changes or failures.

18.6 Implemented Standards

The Ethernet model operates according to the following standards:

- Ethernet: IEEE 802.3-1998
- Fast Ethernet: IEEE 802.3u-1995
- Full-Duplex Ethernet with Flow Control: IEEE 802.3x-1997
- Gigabit Ethernet: IEEE 802.3z-1998

CHAPTER

NINETEEN

THE 802.11 MODEL

19.1 Overview

IEEE 802.11 a.k.a. WiFi is the most widely used and universal wireless networking standard. Specifications are updated every few years, adding more features and ever increasing bit rates.

In INET, nodes become WiFi-enabled by adding a Ieee80211Interface to them. (As mentioned earlier, WirelessHost and AdhocHost already contain one in their default configuration.) APs are represented with the AccessPoint node type. WiFi networks require a matching transmission medium module to be present in the network, which is usually a Ieee80211ScalarRadioMedium.

Operation mode (infrastructure vs ad hoc) is determined by the ingredients of the wireless interface. Ieee80211Interface has the following submodules (incomplete list):

1. *management*: performs association/disassociation with access points, channel scanning, beaconing
2. *agent*: initiates actions such as channel scanning and connecting to and disconnecting from access points
3. *MAC*: transmits and receives frames according to the IEEE 802.11 medium access procedure
4. *PHY*: represents the radio

The management component has several implementations which differ in their role and level of detail:

- Ieee80211MgmtAdhoc: for ad hoc mode stations
- Ieee80211MgmtSta, Ieee80211MgmtStaSimplified: for infrastructure mode stations
- Ieee80211MgmtAp, Ieee80211MgmtApSimplified: for access points

The "simplified" ones assume that stations are statically associated to an access point for the entire duration of the simulation (the scan-authenticate-associate process is not simulated), so they cannot be used e.g. in experiments involving handover.

Ieee80211MgmtSta is does not take any action by itself, it requires an agent (Ieee80211AgentSta or a custom one) to initiate actions.

The following sections examine the above components.

19.2 MAC

The Ieee80211Mac module type represents the IEEE 802.11 MAC. The implementation is entirely based on the standard IEEE 802.11-2012 Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications.

Ieee80211Mac performs transmission of frames according to the CSMA/CA protocol. It receives data and management frames from the upper layers, and transmits them.

The Ieee80211Mac was designed to be modular to facilitate experimenting with new policies, features and algorithms within the MAC layer. Users can easily replace individual components with their own implementations. Policies, which most likely to be experimented with, are extracted into their own modules.

The model has the following replaceable built-in policies:

- ACK policy
- RTS/CTS policy
- Originator and recipient block ACK agreement policies
- MSDU aggregation policy
- Fragmentation policy

The new model also separates the following components:

- Coordination functions
- Channel access methods
- MAC data services
- Aggregation and deaggregation
- Fragmentation and defragmentation
- Block ACK agreements and reordering
- Frame exchange sequences
- Duplicate removal
- Rate selection
- Rate control
- Protection mechanisms
- Recovery procedure
- Contention
- Frame queues
- TX/RX

19.3 Physical Layer

The physical layer modules (Ieee80211Radio) deal with modelling transmission and reception of frames. They model the characteristics of the radio channel, and determine if a frame was received correctly (that is, it did not suffer bit errors due to low signal power or interference in the radio channel). Frames received correctly are passed up to the MAC.

On the physical layer, one can choose from several radios with different levels of detail. The various radio types (with the matching transmission medium types in parentheses) are:

- Ieee80211ScalarRadio (Ieee80211ScalarRadioMedium)
- Ieee80211DimensionalRadio (Ieee80211DimensionalRadioMedium)
- Ieee80211UnitDiskRadio (UnitDiskRadioMedium)

19.4 Management

The management layer exchanges management frames via the MAC with its peer management entities in other STAs and APs. Beacon, Probe Request/Response, Authentication, Association Request/Response etc frames are generated and interpreted by management entities, and transmitted/received via the MAC layer. During scanning, it is the management entity that periodically switches channels, and collects information from received beacons and probe responses.

The management layer has several implementations which differ in their role (STA/AP/ad-hoc) and level of detail: Ieee80211MgmtAdhoc, Ieee80211MgmtAp, Ieee80211MgmtApSimplified, Ieee80211MgmtSta, Ieee80211MgmtStaSimplified. The ..Simplified ones differ from the others in that they do not model the scan-authenticate-associate process, so they cannot be used in experiments involving handover.

19.5 Agent

The agent is what instructs the management layer to perform scanning, authentication and association. The management layer itself just carries out these commands by performing the scanning, authentication and association procedures, and reports back the results to the agent.

The agent component is currently only needed with the Ieee80211MgmtSta module. The managament entities in other NIC variants do not have as much freedom as to need an agent to control them.

Ieee80211MgmtSta requires a Ieee80211AgentSta or a custom agent. By modifying or replacing the agent, one can alter the dynamic behaviour of STAs in the network, for example implement different handover strategies.

CHAPTER

TWENTY

THE 802.15.4 MODEL

20.1 Overview

IEEE 802.15.4 is a technical standard which defines the operation of low-rate wireless personal area networks (LR-WPANs). IEEE 802.15.4 was designed for data rates of 250 kbit/s or lower, in order to achieve long battery life (months or even years) and very low complexity. The standard specifies the physical layer and media access control.

IEEE 802.15.4 is the basis for the ZigBee, ISA100.11a, WirelessHART, MiWi, SNAP,and the Thread specifications, each of which further extends the standard by developing the upper layers which are not defined in IEEE 802.15.4. Alternatively, it can be used with 6LoWPAN, the technology used to deliver IPv6 over WPANs, to define the upper layers. (Thread is also 6LoWPAN-based.)

The INET Framework contains a basic implementation of IEEE 802.15.4 protocol.

20.2 Network Interfaces

There are two network interfaces that differ in the type of radio:

- Ieee802154NarrowbandInterface is for use with narrowband radios
- Ieee802154UwbIrInterface is for use with the UWB-IR radio

To create a wireless node with a 802.15.4 interface, use a node type that has a wireless interface, and set the interface type to the appropriate type. For example, WirelessHost is a node type which is preconfigured to have one wireless interface, `wlan[0]`. `wlan[0]` is of parametric type, so if you build the network from WirelessHost nodes, you can configure all of them to use 802.15.4 with the following line in the ini file:

```
**.wlan[0].typename = "Ieee802154NarrowbandInterface"
```

20.3 Physical Layer

The IEEE 802.15.4 standard defines several alternative PHYs. There are several narrowband radios at various frequency bands using various modulation schemes (DSSS, O-QPSK, MPSK, GFSK BPSK, etc.), a Direct Sequence ultra-wideband (UWB), and one using chirp spread spectrum (CSS).

INET provides the following radios:

- Ieee802154NarrowbandScalarRadio is currently a partially parameterized version of the APSK radio. Before using this radio, one must check its parameters and make sure that they correspond to the specification of the 802.15.4 narrowband PHY to be simulated.
- Ieee802154UwbIrRadio models the 802.14.5 UWB radio.

One must choose a matching medium model, for example Ieee802154UwbIrRadioMedium for Ieee802154UwbIrRadio, and Ieee802154NarrowbandScalarRadioMedium for Ieee802154NarrowbandScalarRadio.

20.4 MAC Protocol

The 802.15.4 MAC is based on collision avoidance via CSMA/CA. Important other features include real-time suitability by reservation of guaranteed time slots, and integrated support for secure communications. Devices also include power management functions such as link quality and energy detection.

The Ieee802154Mac type in INET is currently a parameterized version of a generic CSMA/CA protocol model with ACK support.

There is also a Ieee802154NarrowbandMac.

CHAPTER

TWENTYONE

MAC PROTOCOLS FOR WIRELESS SENSOR NETWORKS

21.1 Overview

The INET Framework contains the implementation of several MAC protocols for wireless sensor networks (WSNs), including B-MAC, L-MAC and X-MAC.

To create a wireless node with a specific MAC protocol, use a node type that has a wireless interface, and set the interface type to the appropriate type. For example, WirelessHost is a node type which is preconfigured to have one wireless interface, `wlan[0]`. `wlan[0]` is of parametric type, so if you build the network from WirelessHost nodes, you can configure all of them to use e.g. B-MAC with the following line in the ini file:

```
**.wlan[0].typename = "BMacInterface"
```

21.2 B-MAC

B-MAC (Berkeley MAC) is a carrier sense media access protocol for wireless sensor networks that provides a flexible interface to obtain ultra low power operation, effective collision avoidance, and high channel utilization. To achieve low power operation, B-MAC employs an adaptive preamble sampling scheme to reduce duty cycle and minimize idle listening. B-MAC is designed for low traffic, low power communication, and is one of the most widely used protocols (e.g. it is part of TinyOS).

The BMac module type implements the B-MAC protocol.

BMacInterface is a WirelessInterface with the MAC type set to BMac.

21.3 L-MAC

L-MAC (Lightweight MAC) is an energy-efficient medium acces protocol designed for wireless sensor networks. Although the protocol uses TDMA to give nodes in the WSN the opportunity to communicate collision-free, the network is self-organizing in terms of time slot assignment and synchronization. The protocol reduces the number of transceiver state switches and hence the energy wasted in preamble transmissions.

The LMac module type implements the L-MAC protocol, based on the paper "A lightweight medium access protocol (LMAC) for wireless sensor networks" by van Hoesel and P. Havinga.

LMacInterface is a WirelessInterface with the MAC type set to LMac.

21.4 X-MAC

X-MAC is a low-power MAC protocol for wireless sensor networks (WSNs). In contrast to B-MAC which employs an extended preamble and preamble sampling, X-MAC uses a shortened preamble that reduces latency at each hop and improves energy consumption while retaining the advantages of low power listening, namely low power communication, simplicity and a decoupling of transmitter and receiver sleep schedules.

The XMac module type implements the X-MAC protocol, based on the paper "X-MAC: A Short Preamble MAC Protocol for Duty-Cycled Wireless Sensor Networks" by Michael Buettner, Gary V. Yee, Eric Anderson and Richard Han.

XMacInterface is a WirelessInterface with the MAC type set to XMac.

CHAPTER

TWENTYTWO

CLOCK MODEL

22.1 Overview

In most communication network simulations, time is simply modeled as a global quantity. All components of the network share the same time throughout the simulation independently of where they are physically located or how they are logically connected to the network.

In contast, in time sensitive networking, the bookkeeping of time is an essential part, which should be explicitly simulated independently of the underlying global time. The reason is that the differences among the local time of the communication network components significantly affects the simulation results.

In such simulations, hardware clocks are simulated on their own, and communication protocols don't rely on the global value of simulation time, which is in fact unknown in reality, but on the value of their own clocks. With having hardware clocks modeled, it's also often required to use various time synhronization protocols, because clocks tend to drift over time and communication protocols rely on the precision of the clocks they are using.

In INET, the clock model is a completely optional feature, which has no effect on the simulation performance when disabled. Even if the feature is enabled, the usage of clock modules by communication protocols and applications is still optional, and enabling the feature has negligible performance hit when not in use. For testing that the mere usage of a clock has no effect on the simulation results, INET also includes an ideal clock mechanism.

22.2 Clocks

Clocks are implemented as modules, and are used by other modules via direct C++ method calls. Clock modules implement the IClock module interface and the corresponding `IClock` C++ interface.

The C++ interface provides an API similar to the standard OMNeT++ simulation time based scheduling mechanism, but it relies on the underlying clock implementation for (re)scheduling events according to the clock. These events are transparently scheduled for the client module, and they will be delivered to it when the clock timers expire.

The clock API uses the clock time instead of the simulation time as arguments and return values. The interface contains functions such as `getClockTime()`, `scheduleClockEventAt()`, `scheduleClockEventAfter()`, `cancelClockEvent()`.

INET contains optional clock modules (not used by default) at the network node and the network interface levels. The following clock models available:

- IdealClock: clock time is identical to the simulation time.
- OscillatorBaseClock: clock time is the number of oscillator ticks multiplied by the nominal tick length.
- SettableClock: a clock which can be set to a different clock time.

22.3 Clock Time

In order to avoid confusing the simulation time (which is basically unknown to communication protocols and hardware elements) with the clock time maintained by hardware clocks, INET introduces a new C++ type called the `ClockTime`.

This type is pretty much the same as the default `SimTime`, but the two types cannot be implicitly converted into each other. This approach prevents accidentally using clock time where simulation time is needed, and vice versa. Simlarly to how `simtime_t` is an alias for `SimTime`, INET also introduces the `clocktime_t` alias for `ClockTime` type.

For the explicit conversion between clock time and simulation time, one can use the `CLOCKTIME_AS_SIMTIME` and the `SIMTIME_AS_CLOCKTIME` C++ macros. Note that these macros don't change the numerical value, they simply convert between the C++ types.

When the actual clock time is used by a clock, the value may be rounded according to the clock granularity and rounding mode (e.g. OscillatorBaseClock). For example, when a clock with a us granularity is instructed to wait for 100 ns, while its oscillator is right in the middle of its ticking period, it may actually wait for the next tick to happen to start the timer and wait another tick to happen to account for the requested wait time interval.

22.4 Oscillators

The clock interface is quite general in the sense that it allows many different ways to implement it. Nevertheless, the most common way is to use an oscillator based clock model.

An oscillator efficiently models the periodic generation of ticks that are usually counted by a clock module. The tick period is not necessarily constant, it can change over time. Oscillators implement the IOscillator: module interface and the corresponding `IOscillator` C++ interface.

The following oscillator models are available:

- IdealOscillator: generates ticks periodically with a constant length (mostly useful for testing).
- ConstantDriftOscillator: tick length changes proportional to the elapsed simulation time (clock drift).
- RandomDriftOscillator: updates clock drift with a random walk process.

22.5 Clock Users

The easiest way to use a clock in applications and communication protocols is to add a *clockModule* parameter that specifies where the clock module can be found. Then the C++ user module should be simply derived from either `ClockUserModuleBase` or the parameterizable `ClockUserModuleMixin` base classes. The clock can be used via the inherited clock related methods or through the methods of the `IClock` C++ interface on the inherited clock field.

22.6 Clock Events

The clock model requires the use of a specific C++ class called `ClockEvent` to schedule clock timers. It's also allowed to derive new C++ classes from `ClockEvent` if necessary. In any case, clock events must be scheduled and canceled via the `IClock` C++ interface to operate properly.

22.7 Controlling Clocks According to a Scenario

In order to support the simulation of specific scenarios, where the clock time or the oscillator drift must be changed according to a predefined script, INET provides clocks and oscillators that implement the interface required by the ScenarioManager module. This allows the user to update the clock and oscillator state from the ScenarioManager XML script and to also mix these operations with many other supported operations.

For example, the SettableClock model supports setting the clock time and also to optionally reset the oscillator at a specific moment of simulation time as follows:

```
<set-clock at="10 s" module="server.clock" time="1.2 s" reset-oscillator="true"/>
```

The above example means that the clock time of the server node's clock will be set to 1.2 seconds when the simulation time reaches 10 seconds, and the clock's oscillator will restart its duty cycle.

For another example, the ConstantDriftOscillator supports changing the state of the oscillator with the following command:

```
<set-oscillator at="10 us" module="server.clock.oscillator" drift-rate="42 ppm"␣
↪tick-offset="1 us"/>
```

This example simultaneously changes the drift rate and the tick offset of the oscillator in the server node's clock.

CHAPTER

TWENTYTHREE

THE PHYSICAL LAYER

23.1 Overview

Wireless network interfaces contain a radio model component, which is responsible for modeling the physical layer (PHY).[1] The radio model describes the physical device that is capable of transmitting and receiving signals on the medium.

Conceptually, a radio model relies on several sub-models:

- antenna model
- transmitter model
- receiver model
- error model (as part of the receiver model)
- energy consumption model

The antenna model is shared between the transmitter model and the receiver model. The separation of the transmitter model and the receiver model allows asymmetric configurations. The energy consumer model is optional, and it is only used when the simulation of energy consumption is necessary.

23.2 Generic Radio

In INET, radio models implement the IRadio module interface. A generic, often used implementation of IRadio is the Radio NED type. Radio is an active compound module, that is, it has an associated C++ class that encapsulates the computations.

Radio contains its antenna, transmitter, receiver and energy consumer models as submodules with parametric types:

```
antenna: <default("IsotropicAntenna")> like IAntenna;
transmitter: <> like ITransmitter;
receiver: <> like IReceiver;
energyConsumer: <default("")> like IEnergyConsumer
    if typename != "";
```

The following sections describe the parts of the radio model.

[1] Wired network interfaces could similarly contain an explicit PHY model. The reason they do not is that wired links normally have very low error rates and simple observable behavior, and there is usually not much to be gained from modeling the physical layer in detail.

23.3 Components of a Radio

23.3.1 Antenna Models

The antenna model describes the effects of the physical device which converts electric signals into radio waves, and vice versa. This model captures the antenna characteristics that heavily affect the quality of the communication channel. For example, various antenna shapes, antenna size and geometry, antenna arrays, and antenna orientation causes different directional or frequency selectivity.

The antenna model provides a position and an orientation using a mobility model that defaults to the mobility of the node. The main purpose of this model is to compute the antenna gain based on the specific antenna characteristics and the direction of the signal. The signal direction is computed by the medium from the position and the orientation of the transmitter and the receiver. The following list provides some examples:

- IsotropicAntenna: antenna gain is exactly 1 in any direction
- ConstantGainAntenna: antenna gain is a constant determined by a parameter
- DipoleAntenna: antenna gain depends on the direction according to the dipole antenna characteristics
- InterpolatingAntenna: antenna gain is computed by linear interpolation according to a table indexed by the direction angles

23.3.2 Transmitter Models

The transmitter model describes the physical process which converts packets into electric signals. In other words, this model converts an L2 frame into a signal that is transmitted on the medium. The conversion process and the representation of the signal depends on the level of detail and the physical characteristics of the implemented protocol.

There are two main levels of detail (or modeling depths):

- In the *flat model*, the transmitter model skips the symbol domain and the sample domain representations, and it directly creates the analog domain representation. The bit domain representation is reduced to the bit length of the packet, and the actual bits are ignored.
- In the *layered model*, the conversion process involves various processing steps such as packet serialization, forward error correction encoding, scrambling, interleaving, and modulation. This transmitter model requires significantly more computation, but it produces accurate bit domain, symbol domain, and sample domain representations.

Some of the transmitter types available in INET:

- UnitDiskTransmitter
- ApskScalarTransmitter
- ApskDimensionalTransmitter
- ApskLayeredTransmitter
- Ieee80211ScalarTransmitter
- Ieee80211DimensionalTransmitter

23.3.3 Receiver Models

The receiver model describes the physical process which converts electric signals into packets. In other words, this model converts a reception, along with an interference computed by the medium model, into a MAC packet and a reception indication.

For a packet to be received successfully, reception must be *possible* (based on reception power, bandwidth, modulation scheme and other characteristics), it must be *attempted* (i.e. the receiver must synchronize itself on the preamble and start receiving), and it must be *successful* (as determined by the error model and the simulated part of the signal decoding).

In the *flat model*, the receiver model skips the sample domain, the symbol domain, and the bit domain representations, and it directly creates the packet domain representation by copying the packet from the transmission. It uses the error model to decide whether the reception is successful.

In the *layered model*, the conversion process involves various processing steps such as demodulation, descrambling, deinterleaving, forward error correction decoding, and deserialization. This reception model requires much more computation than the flat model, but it produces accurate sample domain, symbol domain, and bit domain representations.

Some of the receiver types available in INET:

- UnitDiskReceiver
- ApskScalarReceiver
- ApskDimensionalReceiver
- ApskLayeredReceiver
- Ieee80211ScalarReceiver
- Ieee80211DimensionalReceiver

23.3.4 Error Models

Determining reception errors is a crucial part of the reception process. There are often several different statistical error models in the literature even for a particular physical layer. In order to support this diversity, the error model is a separate replaceable component of the receiver.

The error model describes how the signal to noise ratio affects the amount of errors at the receiver. The main purpose of this model is to determine whether the received packet has errors or not. It also computes various physical layer indications for higher layers such as packet error rate, bit error rate, and symbol error rate. For the layered reception model it needs to compute the erroneous bits, symbols, or samples depending on the lowest simulated physical domain where the real decoding starts. The error model is optional (if omitted, all receptions are considered successful.)

The following list provides some examples:

- StochasticErrorModel: simplistic error model with constant symbol/bit/packet error rates as parameters; suitable for testing.
- ApskErrorModel
- Ieee80211NistErrorModel, Ieee80211YansErrorModel, Ieee80211BerTableErrorModel: various error models for IEEE 802.11 network interfaces.

23.3.5 Power Consumption Models

A substantial part of the energy consumption of communication devices comes from transmitting and receiving signals. The energy consumer model describes how the radio consumes energy depending on its activity. This model is optional (if omitted, energy consumption is ignored.)

The following list provides some examples:

- StateBasedEpEnergyConsumer: power consumption is determined by the radio state (a combination of radio mode, transmitter state and receiver state), and specified in parameters like `receiverIdlePowerConsumption` and `receiverReceivingDataPowerConsumption`, in watts.
- StateBasedCcEnergyConsumer: similar to the previous one, but consumption is given in ampères.

23.4 Layered Radio Models

In layered radio models, the transmitter and receiver models are split to several stages to allow more fine-grained modeling.

For transmission, processing steps such as packet serialization, forward error correction (FEC) encoding, scrambling, interleaving, and modulation are explicitly modeled. Reception involves the inverse operations: demodulation, descrambling, deinterleaving, FEC decoding, and deserialization.

In layered radio models, these processing steps are encapsulated in four stages, represented as four submodules in both the transmitter and receiver model:

1. *Encoding and Decoding* describe how the packet domain signal representation is converted into the bit domain, and vice versa.
2. *Modulation and Demodulation* describe how the bit domain signal representation is converted into the symbol domain, and vice versa.
3. *Pulse Shaping and Pulse Filtering* describe how the symbol domain signal representation is converted into the sample domain, and vice versa.
4. *Digital Analog and Analog Digital Conversion* describe how the sample domain signal representation is converted into the analog domain, and vice versa.

In layered radio transmitters and receivers such as ApskLayeredTransmitter and ApskLayeredReceiver, these submodules have parametric types to make them replaceable. This provides immense freedom for experimentation.

23.5 Notable Radio Models

The Radio module has several specialized versions derived from it, where certain submodule types and parameters are set to fixed values. This section describes some of the frequently used ones.

The radio can be replaced in wireless network interfaces by setting the `typename` parameter of the radio submodule, like in the following ini file fragment.

```
**.wlan[*].radio.typename = "UnitDiskRadio"
```

However, be aware that not all MAC protocols can be used with all radio models, and that some radio models require a matching transmission medium module.

23.5.1 UnitDiskRadio

UnitDiskRadio provides a very simple but fast and predictable physical layer model. It is the implementation (with some extensions) of the *Unit Disk Graph* model, which is widely used for the study of wireless ad-hoc networks. UnitDiskRadio is applicable if network nodes need to have a finite communication range, but physical effects of signal propagation are to be ignored.

UnitDiskRadio allows three radii to be given as parameters, instead of the usual one: communication range, interference range, and detection range. One can also turn off interference modeling (meaning that signals colliding at a receiver will all be received correctly), which is sometimes a useful abstraction.

UnitDiskRadio needs to be used together with a special physical medium model, UnitDiskRadioMedium.

The following ini file fragment shows an example configuration.

```
*.radioMedium.typename = "UnitDiskRadioMedium"
*.host[*].wlan[*].radio.typename = "UnitDiskRadio"
*.host[*].wlan[*].radio.transmitter.bitrate = 2Mbps
*.host[*].wlan[*].radio.transmitter.preambleDuration = 0s
*.host[*].wlan[*].radio.transmitter.headerLength = 96b
*.host[*].wlan[*].radio.transmitter.communicationRange = 100m
*.host[*].wlan[*].radio.transmitter.interferenceRange = 0m
*.host[*].wlan[*].radio.transmitter.detectionRange = 0m
*.host[*].wlan[*].radio.receiver.ignoreInterference = true
```

As a side note, if modeling full connectivity and ignoring interference is required, then ShortcutInterface provides an even simpler and faster alternative.

23.5.2 APSK Radio

APSK radio models provide a hypothetical radio that simulates one of the well-known ASP, PSK and QAM modulations. (APSK stands for Amplitude and Phase-Shift Keying.)

APSK radio has scalar/dimensional, and flat/layered variants. The flat variants, ApskScalarRadio and ApskDimensionalRadio model frame transmissons in the selected modulation scheme but without utilizing other techniques such as forward error correction (FEC), interleaving, spreading, etc. These radios require matching medium models, ApskScalarRadioMedium and ApskDimensionalRadioMedium.

The layered versions, ApskLayeredScalarRadio and ApskLayeredDimensionalRadio can not only model the processing steps missing from their simpler counterparts, they also feature configurable level of detail: the transmitter and receiver modules have `levelOfDetail` parameters that control which domains are actually simulated. These radio models must be used in conjuction with ApskLayeredScalarRadioMedium and ApskLayeredDimensionalRadioMedium, respectively.

CHAPTER

TWENTYFOUR

THE TRANSMISSION MEDIUM

24.1 Overview

For wireless communication, an additional module is required to model the shared physical medium where the communication takes place. This module keeps track of transceivers, noise sources, ongoing transmissions, background noise, and other ongoing noises.

It relies on several models:

1. signal propagation model
2. path loss model
3. obstacle loss model
4. background noise model
5. signal analog model

With the help of the above models, the medium module computes when, where, and how signals arrive at receivers, including the set of interfering signals and noises. In addition, the medium module also contains various mechanisms and ways to improve the scalability of wireless network simulations.

24.2 RadioMedium

The standard transmission medium model in INET is RadioMedium. RadioMedium is as an OMNeT++ compound module with several replaceable submodules. It contains submodules for each of the above models (signal propagation, path loss, etc.), and various caches for efficiency.

Note that RadioMedium is an active compound module, that is, it has an associated C++ class that encapsulates the computations.

RadioMedium contains its components as submodules with parametric types:

```
propagation: <default("ConstantSpeedPropagation")> like IPropagation;
analogModel: <default("ScalarAnalogModel")> like IAnalogModel;
backgroundNoise: <default("IsotropicScalarBackgroundNoise")> like␣
↪IRadioBackgroundNoise
    if typename != "";
pathLoss: <default("FreeSpacePathLoss")> like IPathLoss;
obstacleLoss: <default("")> like IObstacleLoss
    if typename != "";
mediumLimitCache: <default("MediumLimitCache")> like IMediumLimitCache;
communicationCache: <default("VectorCommunicationCache")> like ICommunicationCache;
neighborCache: <default("")> like INeighborCache
    if typename != "";
```

There are many preconfigured versions of RadioMedium:

- For use with UnitDiskRadio: UnitDiskRadioMedium

- For APSK radios: ApskScalarRadioMedium, ApskDimensionalRadioMedium, ApskLayeredScalarRadioMedium, ApskLayeredDimensionalRadioMedium,
- For IEEE 802.11: Ieee80211ScalarRadioMedium, Ieee80211DimensionalRadioMedium, Ieee80211LayeredScalarRadioMedium, Ieee80211LayeredDimensionalRadioMedium,
- For IEEE 802.15.4: Ieee802154UwbIrRadioMedium, Ieee802154NarrowbandScalarRadioMedium

The following sections describe the parts of the medium model.

24.3 Propagation Models

When a transmitter starts to transmit a signal, the beginning of the signal propagates through the transmission medium. When the transmitter ends the transmission, the signal's end propagates similarly. The propagation model describes how a signal moves through space over time. Its main purpose is to compute the arrival space-time coordinates at receivers. There are two built-in models in INET, implemented as simple modules:

- ConstantTimePropagation is a simplistic model where the propagation time is independent of the traveled distance. The propagation time is simply determined by a module parameter.
- ConstantSpeedPropagation is a more realistic model where the propagation time is proportional to the traveled distance. The propagation time is independent of the transmitter and receiver movement during both signal transmission and propagation. The propagation speed is determined by a module parameter.

The default propagation model is configured as follows:

```
*.radioMedium.propagation.typename = "ConstantSpeedPropagation" # module type
*.radioMedium.propagation.propagationSpeed = 299792458 mps # speed of light
```

A more accurate model could take into consideration the transmitter and receiver movement. This effect becomes especially important for acoustic communication, because the propagation speed of the signal is much more comparable to the speed of the transceivers.

24.4 Path Loss Models

As a signal propagates through space its power density decreases. This is called path loss and it is the combination of many effects such as free-space loss, refraction, diffraction, reflection, and absorption. There are several different path loss models in the literature, which differ in their parameterization and application area.

In INET, a path loss model is an OMNeT++ simple module implementing a specific path loss algorithm. Its main purpose is to compute the power loss for a given signal, but it is also capable of estimating the range for a given loss. The latter is useful, for example, to allow visualizing communication range. INET contains a number of built-in path loss algorithms, each comes with its own set of parameters:

- FreeSpacePathLoss models line of sight path loss for air or vacuum.
- BreakpointPathLoss refines it using dual slope model with two separate path loss exponents.
- LogNormalShadowing models path loss for a wide range of environments (e.g. urban areas, and buildings)
- TwoRayGroundReflection models interference between line of sight and single ground reflection.
- TwoRayInterference refines the above for inter-vechicle communication.
- RicianFading is a stochastical model for the anomaly caused by partial cancellation of a signal by itself.
- RayleighFading is a stochastical model for heavily built-up urban environments when there is no dominant propagation along the line of sight.
- NakagamiFading further refines the above two models for cellular systems.

The following example replaces the default free-space path loss model with log normal shadowing:

```
*.radioMedium.pathLoss.typename = "LogNormalShadowing" # module type
*.radioMedium.pathLoss.sigma = 1.1 # override default value of 1
```

24.5 Obstacle Loss Models

When the signal propagates through space it also passes through physical objects present in that space. As the signal penetrates physical objects, its power decreases when it reflects from surfaces, and also when it is absorbed by their material. There are various ways to model this effect, which differ in the trade-off between accuracy and performance.

In INET, an obstacle loss model is an OMNeT++ simple module. Its main purpose is to compute the power loss based on the traveled path and the signal frequency. The obstacle loss models most often use the physical environment model to determine the set of penetrated physical objects. INET contains a few built-in obstacle loss models:

- IdealObstacleLoss model determines total or no power loss at all by checking if there is any obstructing physical object along the straight propagation path.
- DielectricObstacleLoss computes the power loss based on the accurate dielectric and reflection loss along the straight path considering the shape, position, orientation, and material of obstructing physical objects.

By default, the medium module doesn't contain any obstacle loss model, but configuring one is very simple:

```
*.radioMedium.obstacleLoss.typename = "DielectricObstacleLoss" # module type
```

Statistical obstacle loss models are also possible but currently not provided.

24.6 Background Noise Models

Thermal noise, cosmic background noise, and other random fluctuations of the electromagnetic field affect the quality of the communication channel. This kind of noise doesn't come from a particular source, so it doesn't make sense to model its propagation through space. The background noise model describes instead how it changes over space and time.

In INET, a background noise model is an OMNeT++ simple module. Its main purpose is to compute the analog representation of the background noise for a given space-time interval. For example, IsotropicScalarBackgroundNoise computes a background noise that is independent of space-time coordinates, and its scalar power is determined by a module parameter.

The simplest background noise model can be configured as follows:

```
*.radioMedium.backgroundNoise.typename = "IsotropicScalarBackgroundNoise" # type
*.radioMedium.backgroundNoise.power = -110 dBm # isotropic scalar noise power
```

24.7 Analog Models

The analog signal is a complex physical phenomenon which can be modeled in many different ways. Choosing the right analog domain signal representation is the most important factor in the trade-off between accuracy and performance. The analog model of the transmission medium determines how signals are represented while being transmitted, propagated, and received.

In INET, an analog model is an OMNeT++ simple module. Its main purpose is to compute the received signal from the transmitted signal. The analog model combines the effect of the antenna, path loss, and obstacle loss models. Transceivers must be configured transmit and receive signals according to the representation used by the analog model.

The most commonly used analog model, which uses a scalar signal power representation over a frequency and time interval, can be configured as follows:

```
*.radioMedium.analogModel.typename = "ScalarAnalogModel" # module type
```

24.8 Neighbor Cache

Transceivers are considered neighbors if successful communication is possible between them. For wired communication it is easy to determine which transceivers are neighbors, because they are connected by wires. In contrast, in wireless communication determining which transceivers are neighbors isn't obvious at all.

In INET, a neighbor cache is an OMNeT++ simple module which provides an efficient way of keeping track of the neighbor relationship between transceivers. Its main purpose is to compute the set of affected receivers for a given transmission. All built-in models in INET provide a conservative approximation only, because they update their state periodically:

- NeighborListNeighborCache takes a range as parameter, and for each transceiver it maintains the list of receivers within range (*neighbor list*).
- GridNeighborCache organizes transceivers in a 3D grid with constant cell size.
- QuadTreeNeighborCache organizes transceivers in a 2D quad tree (ignoring the Z axis) with constant node size.

The following example sets QuadTreeNeighborCache as neighbor cache:

```
**.radioMedium.neighborCache.typename = "QuadTreeNeighborCache" # module type
**.radioMedium.neighborCache.maxNumOfPointsPerQuadrant = 4 # affects tree depth
```

How should one decide which neighbor cache to choose for a given simulation? As the sole purpose of the neighbor cache is to speed up the simulation, one should choose the one that leads to the best performance for that particular network. Which one performs best is best determined by experimentation, as it depends on many factors: number of nodes, their spatial distribution, their speed and movement pattern, their communication pattern, and so on. Note that not only the choice of neighbor cache but also its parameterization can affect performance.

24.9 Medium Limit Cache

The medium limit cache (and its default implementation MediumLimitCache) keeps track of certain thresholds and minimum/maximum values of quantities related to layer 1 modeling. Some of these limits can be gathered from other modules in the network, but still, all of them can be explicitly specified by the user. The quantities include:

- maximum speed (can be gathered from mobility models)
- maximum transmission power
- minimum interference power and reception power
- maximum antenna gain (can be computed from antenna models)
- minimum time interval to consider two overlapping signals interfering
- maximum duration of a transmission
- maximum communication range and interference range (can be computed from transmitter and receiver models)

These limits allow the transmission medium model to make assumptions about the locations of nodes (i.e. the maximum distance they can move during some interval), about the possibility of interference, and about the possibility of a signal being receivable.

24.10 Communication Cache

The communication cache is used to cache various intermediate computation results related to the communication on the medium. The main motivation to have multiple implementations is that different implementations may be the most efficient in different simulations. Also, a conservative (simple but robust) implementation may be used for validating new (more efficient but also more complex) implementations.

Implementations include:

- ReferenceCommunicationCache
- MapCommunicationCache
- VectorCommunicationCache

24.11 Improving Scalability

The simulation of wireless networks is inherently less scalable than that of wired networks. In wired networks, a transmission only affects the host's neighbors on the link, which is usually 1 in modern networks that are dominated by point-to-point links. The wireless medium, however, is a broadcast medium. Any transmission is "heard" by all nodes within interference range, not only the intended recipients. The signal may be receivable by them (and must be indeeded received before the destination address field in it can be examined), or may interfere with the reception of other transmissions. Whichever the case, the transmission must be evaluated or processed by a much larger number of nodes than in the wired case. This makes the computational complexity at least $O(n^2)$ (n being the number of nodes.) Other effects may further increase the exponent.

The medium module provides a set of parameters that can be used to alleviate the scalability issue. These *filter* parameters that can be used to reduce the amount of processing at nodes that are not the indended recipients of the frame, increasing simulation performance.

There are several filters that can be enabled/disabled individually:

- *Range filter*. When this filter is active, the medium module does not send signals to a radio if it is outside interference range (or communication range, this option can also be selected.)
- *Radio mode filter*. When this filter is active, the medium module does not send signals to a radio if it is neither in *receiver* nor in *transceiver* mode.
- *Listening filter*. When this filter is active, the medium module does not send signals to a radio if it listens on the channel in incompatible mode (e.g. different carrier frequency and bandwidth, or different modulation)
- *MAC address filter*. When this filter is active, the radio medium does not send signals to a radio if it the destination MAC address does not match

The corresponding module parameters are called `rangeFilter`, `radioModeFilter`, `listeningFilter` and `macAddressFilter`. By default, all filters are turned off.

CHAPTER

TWENTYFIVE

THE PHYSICAL ENVIRONMENT

25.1 Overview

Wireless networks are heavily affected by the physical environment, and the requirements for today's ubiquitous wireless communication devices are increasingly demanding. Cellular networks serve densely populated urban areas, wireless LANs need to be able to cover large buildings with several offices, low-power wireless sensors must tolerate noisy industrial environments, batteries need to remain operational under various external conditions, and so on.

The propagation of radio signals, the movement of communicating agents, battery exhaustion, etc., depend on the surrounding physical environment. For example, signals can be absorbed by objects, can pass through objects, can be refracted by surfaces, can be reflected from surfaces, or battery capacity might depend on external temperature. These effects cannot be ignored in high-fidelity simulations.

In order to help the modeling process, the model of the physical environment in the INET Framework is separated from the rest of the simulation model. The main goal of the physical environment model is to describe buildings, walls, vegetation, terrain, weather, and other physical objects and conditions that might have effects on radio signal propagation, movement, batteries, etc. This separation makes the model reusable by all other simulation models that depend on these circumstances.

The following sections provide a brief overview of the physical environment model.

25.2 PhysicalEnvironment

In INET, the physical environment is modeled by the PhysicalEnvironment compound module. This module normally has one instance in the network, and acts as a database that other parts of the simulation can query at runtime. It contains the following information:

- geometry and properties of *physical objects* (usually referrred to as "obstacles" in wireless simulations)
- a *ground model*
- other physical properties of the environment, like its bounds in space

PhysicalEnvironment is an active compound module, that is, it has an associated C++ class that contains the data structures and implements an API that allows other modules to query the data.

Part of PhysicalEnvironment's functionality is implemented in submodules for easy replacement. They are currently the ground model, and an object cache (for efficient queries):

```
ground: <default("")> like IGround if typename != "";
objectCache: <default("")> like IObjectCache if typename != "";
```

25.3 Physical Objects

The most important aspect of the physical environment is the objects which are present in it. For example, simulating an indoor Wifi scenario may need to model walls, floors, ceilings, doors, windows, furniture, and similar objects, because they all affect signal propagation (obstacle modeling).

Objects are located in space, and have shapes and materials. The physical environment model supports basic shapes and homogeneous materials, which is a simplified description but still allows for a reasonable approximation of reality. Physical objects in INET have the following properties:

- *shape* describes the object in 3D independent of its position and orientation.
- *position* determines where the object is located in the 3D space.
- *orientation* determines how the object is rotated relative to its default orientation.
- *material* describes material specific physical properties.
- *graphical properties* provide parameters for better visualization.

Graphical properties include:

- *line width*: affects surface outline
- *line color*: affects surface outline
- *fill color*: affects surface fill
- *opacity*: affects surface outline and fill
- *tags*: allows filtering objects on the graphical user interface

Physical objects in INET are stationary, they cannot change their position or orientation over time. Since the shape of the physical objects might be quite diverse, the model is designed to be extensible with new shapes. INET provides the following shapes:

- *sphere* shapes are specified by a radius
- *cuboid* shapes are specified by a length, a width, and a height
- *prism* shapes are specified by a 2D polygon base and a height
- *polyhedron* shapes are specified by the convex hull of a set of 3D vertices

The following example shows how to define various physical objects using the XML syntax supported by the physical environment:

```
<environment>
  <!-- shapes and materials -->
  <shape id="1" type="sphere" radius="10"/>
  <shape id="2" type="cuboid" size="20 30 40"/>
  <shape id="3" type="prism" height="10" points="0 0 10 0 10 10 0 10"/>
  <shape id="4" type="polyhedron" points="0 0 0 10 0 0 10 10 0 0 10 0 ..."/>
  <material id="1" resistivity="10" relativePermittivity="4.5"/>
  <!-- an object that uses a previously defined shape and material -->
  <object position="min 10 20 0" orientation="45 0 0" shape="1" material="1"/>
  <!-- an object defined with an in-line shape -->
  <object position="min 10 20 0" orientation="45 -30 0" shape="cuboid 20 30 40"
          material="concrete" line-color="0 0 0" fill-color="112 128 144"/>
</environment>
```

In order to load the above XML file, the following configuration could be used:

```
*.physicalEnvironment.config = xmldoc("objects.xml") # load physical objects
```

25.4 Ground Models

In inter-vehicle simulations the terrain has profound effects on signal propagation. For example, vehicles on the opposite sides of a mountain cannot directly communicate with each other.

A ground model describes the 3D surface of the terrain. Its main purpose is to compute a position on the surface underneath an particular position.

INET contains the following built-in ground models implemented as OMNeT++ simple modules:

- FlatGround is a trivial model which provides a flat surface parallel to the XY plane at a certain height.
- OsgEarthGround is a more realistic model (based on) which provides a terrain surface.

25.5 Geographic Coordinate System Models

In order to run high fidelity simulations, it is often required to embed the communication network into a real world map. With the new OMNeT++ 5 version, INET already provides support for 3D maps using for visualization and as the map provider.

However, INET carries out all geometric computation internally (including signal propagation and path loss) in a 3D Euclidean coordinate system. The discrepancy between the internal scene coordinate system and the usual geographic coordinate systems must be resolved.

A geographic coordinate system model maps scene coordinates to geographic coordinates, and vice versa. Such a model allows positioning physical objects and describing network node mobility using geographical coordinates (e.g longitude, latitude, altitude).

In INET, a geographic coordinate system model is implemented as an OMNeT++ simple module:

- SimpleGeographicCoordinateSystem provides a trivial linear approximation without any external dependency.
- OsgGeographicCoordinateSystem provides an accurate mapping using the external library.

In order to use geographic coordinates in a simulation, a geographic coordinate system module must be included in the network. The desired physical environment module and mobility modules must be configured (using module path parameters) to use the geographic coordinate system module. The following example also shows how the geographic coordinate system module can be configured to place the scene at a particular geographic location and orientation.

```
*.physicalEnvironment.coordinateSystemModule = "coordinateSystem" # reference
*.*.mobility.coordinateSystemModule = "coordinateSystem" # reference
*.coordinateSystem.sceneLongitude = -71.070421deg # scene origin
*.coordinateSystem.sceneLatitude = 42.357824deg # scene origin
*.coordinateSystem.sceneHeading = 68.3deg # scene orientation
```

25.6 Object Cache

If a simulation contains a large number of physical objects, then signal propagation may become computationally very expensive. The reason is that the transmission medium model must check each line of sight path between all transmitter and receiver pairs against all physical objects.

An object cache organizes physical objects into a data structure which provides efficient geometric queries. Its main purpose is to iterate all physical objects penetrated by a 3D line segment.

In INET, an object cache model is implemented as an OMNeT++ simple module:

- GridObjectCache organizes objects into a fixed cell size 3D spatial grid.
- BvhObjectCache organizes objects into a tree data structure based on recursive 3D volume division.

CHAPTER

TWENTYSIX

NODE MOBILITY

26.1 Overview

In order to simulate ad-hoc wireless networks, it is important to model the motion of mobile network nodes. Received signal strength, signal interference, and channel occupancy depend on the distances between nodes. The selected mobility models can significantly influence the results of the simulation (e.g. via packet loss rates).

A mobility model describes position and orientation over time in a 3D Euclidean coordinate system. Its main purpose is to provide position, velocity and acceleration, and also angular position, angular velocity, and angular acceleration data as three-dimensional quantities at the current simulation time.

In INET, a mobility model is most often an OMNeT++ simple module implementing the motion as a C++ algorithm. Although most models have a few common parameters (e.g. for initial positioning), they always come with their own set of parameters. Some models support geographic positioning to ease the configuration of map based scenarios.

Mobility models be *single* or *group* mobility models. Single mobility models describe the motion of entities independent of each other. Group mobility models provide such a motion where group members are dependent on each other.

Mobility models can also be categorized as *trace-based*, *deterministic*, *stochastic*, and *combining* models.

26.1.1 Using Mobility Models

In order for a mobility model to actually have an effect on the motion of a network node, the mobility model needs to be included as a submodule in the compound module of the network node. By default, a transceiver antenna within a network node uses the same mobility model as the node itself, but that is completely optional. For example, it is possible to model a vehicle facing forward while moving on a road that contains multiple transceiver antennas at different relative locations with different orientations.

26.1.2 The Scene

Many mobility models allow the user to define a cubic volume that the node can not leave. The volume is configured by setting the `constraintAreaX`, `constraintAreaY`, `constraintAreaZ`, `constraintAreaWidth`, `constraintAreaHeight` and `constraintAreaDepth` parameters.

If the `initFromDisplayString` parameter, the initial position is taken from the display string. Otherwise, the position can be given in the `initialX`, `initialY` and `initialZ` parameters. If neither of these parameters are given, a random initial position is choosen within the contraint area.

When the node reaches the boundary of the constraint area, the mobility component has to prevent the node to exit. Many mobility models offer the following policies:

- reflect of the wall
- reappear at the opposite edge (torus area)
- placed at a randomly chosen position of the area

- stop the simulation with an error

26.2 Built-In Mobility Models

26.2.1 List of Mobility Models

The following, potentially list contains the mobility models available in INET. Nearly all of these models als single mobility models; group mobility can be implemented e.g. with combining other mobility models.

Stationary

Stationary models only define position (and orientation), but no motion.

- StationaryMobility provides deterministic and random positioning.
- StaticGridMobility places several mobility models in a rectangular grid.
- StaticConcentricMobility places several models in a set of concentric circles.

Deterministic

Deterministic mobility models use non-random mathematical models for describing motion.

- LinearMobility moves linearly with a constant speed or constant acceleration.
- CircleMobility moves around a circle parallel to the XY plane with constant speed.
- RectangleMobility moves around a rectangular area parallel to the XY plane with constant speed.
- TractorMobility moves similarly to a tractor on a field with a number of rows.
- VehicleMobility moves similarly to a vehicle along a path especially turning around corners.
- TurtleMobility moves according to an XML script written in a simple yet expressive LOGO-like programming language.
- FacingMobility orients towards the position of another mobility model.

Trace-Based

Trace-based mobility models replay recorded motion as observed in real life.

- BonnMotionMobility replays trace files of the BonnMotion scenario generator.
- Ns2MotionMobility replays files of the CMU's scenario generator used in ns2.
- AnsimMobility replays XML trace files of the ANSim (Ad-Hoc Network Simulation) tool.

Stochastic

Stochastic or random mobility models use mathematical models involving random numbers.

- RandomWaypointMobility moves to random destination with random speed.
- GaussMarkovMobility uses one parameter to vary the degree of randomness from linear to Brown motion.
- MassMobility moves similarly to a mass with inertia and momentum.
- ChiangMobility uses a probabilistic transition matrix to change the motion state.

Combining

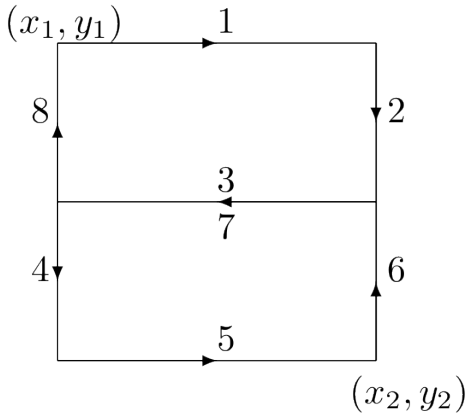
Combining mobility models are not mobility models per se, but instead, they allow more complex motions to be formed from simpler ones via superposition and other ways.

- SuperpositioningMobility model combines several other mobility models by summing them up. It allows creating group mobility by sharing a mobility model in each group member, separating initial positioning from positioning during the simulation, and separating positioning from orientation.
- AttachedMobility models a mobility that is attached to another one at a given offset. Position, velocity and acceleration are all affected by the respective quantites and also the orientation of the referenced mobility.

26.2.2 More Information on Some Mobility Models

TractorMobility

Moves a tractor through a field with a certain amount of rows. The following figure illustrates the movement of the tractor when the `rowCount` parameter is 2. The trajectory follows the segments in `1,2,3,4,5,6,7,8,1,2,3...` order. The area is configured by the `x1`, `y1`, `x2`, `y2` parameters.



RandomWaypointMobility

In the Random Waypoint mobility model the nodes move in line segments. For each line segment, a random destination position (distributed uniformly over the scene) and a random speed is chosen. You can define a speed as a variate from which a new value will be drawn for each line segment; it is customary to specify it as `uniform(minSpeed, maxSpeed)`. When the node reaches the target position, it waits for the time `waitTime` which can also be defined as a variate. After this time the the algorithm calculates a new random position, etc.

GaussMarkovMobility

The Gauss-Markov model contains a tuning parameter that control the randomness in the movement of the node. Let the magnitude and direction of speed of the node at the nth time step be s_n and d_n. The next speed and direction are computed as

$$s_{n+1} = \alpha s_n + (1-\alpha)\bar{s} + \sqrt{(1-\alpha^2)}s_{x_n}$$

$$d_{n+1} = \alpha s_n + (1-\alpha)\bar{d} + \sqrt{(1-\alpha^2)}d_{x_n}$$

where $\bar{s}$ and $\bar{d}$ are constants representing the mean value of speed and direction as $n \to \infty$; and s_{x_n} and d_{x_n} are random variables with Gaussian distribution.

Totally random walk (Brownian motion) is obtained by setting $\alpha = 0$, while $\alpha = 1$ results a linear motion.

To ensure that the node does not remain at the boundary of the constraint area for a long time, the mean value of the direction ($\bar{d}$) modified as the node enters the margin area. For example at the right edge of the area it is set to 180 degrees, so the new direction is away from the edge.

MassMobility

This is a random mobility model for a mobile host with a mass. It is the one used in [**?**].

> "An MH moves within the room according to the following pattern. It moves along a straight line for a certain period of time before it makes a turn. This moving period is a random number, normally distributed with average of 5 seconds and standard deviation of 0.1 second. When it makes a turn, the new direction (angle) in which it will move is a normally distributed random number with average equal to the previous direction and standard deviation of 30 degrees. Its speed is also a normally distributed random number, with a controlled average, ranging from 0.1 to 0.45 (unit/sec), and standard deviation of 0.01 (unit/sec). A new such random number is picked as its speed when it makes a turn. This pattern of mobility is intended to model node movement during which the nodes have momentum, and thus do not start, stop, or turn abruptly. When it hits a wall, it reflects off the wall at the same angle; in our simulated world, there is little other choice."

This implementation can be parameterized a bit more, via the `changeInterval`, `changeAngleBy` and `changeSpeedBy` parameters. The parameters described above correspond to the following settings:

- changeInterval = normal(5, 0.1)
- changeAngleBy = normal(0, 30)
- speed = normal(avgSpeed, 0.01)

ChiangMobility

Implements Chiang's random walk movement model ([**?**]). In this model, the state of the mobile node in each direction (x and y) can be:

- 0: the node stays in its current position
- 1: the node moves forward
- 2: the node moves backward

The (i, j) element of the state transition matrix determines the probability that the state changes from i to j:

$$\begin{pmatrix} 0 & 0.5 & 0.5 \\ 0.3 & 0.7 & 0 \\ 0.3 & 0 & 0.7 \end{pmatrix}$$

26.2.3 Replaying trace files

BonnMotionMobility

Uses the native file format of BonnMotion.

The file is a plain text file, where every line describes the motion of one host. A line consists of one or more (t, x, y) triplets of real numbers, like:

```
t1 x1 y1 t2 x2 y2 t3 x3 y3 t4 x4 y4 ...
```

The meaning is that the given node gets to (xk, yk) at tk. There's no separate notation for wait, so x and y coordinates will be repeated there.

Ns2MotionMobility

Nodes are moving according to the trace files used in NS2. The trace file has this format:

```
# '#' starts a comment, ends at the end of line
$node_(<id>) set X_ <x> # sets x coordinate of the node identified by <id>
$node_(<id>) set Y_ <y> # sets y coordinate of the node identified by <id>
$node_(<id>) set Z_ <z> # sets z coordinate (ignored)
$ns at $time "$node_(<id>) setdest <x> <y> <speed>" # at $time start moving
towards <x>,<y> with <speed>
```

The Ns2MotionMobility module has the following parameters:

- `traceFile` the Ns2 trace file
- `nodeId` node identifier in the trace file; -1 gets substituted by parent module's index
- `scrollX`, `scrollY` user specified translation of the coordinates

ANSimMobility

It reads trace files of the ANSim Tool. The nodes are moving along linear segments described by an XML trace file conforming to this DTD:

```
<!ELEMENT mobility (position_change*)>
<!ELEMENT position_change (node_id, start_time, end_time, destination)>
<!ELEMENT node_id (#PCDATA)>
<!ELEMENT start_time (#PCDATA)>
<!ELEMENT end_time (#PCDATA)>
<!ELEMENT destination (xpos, ypos)>
<!ELEMENT xpos (#PCDATA)>
<!ELEMENT ypos (#PCDATA)>
```

Parameters of the module:

- `ansimTrace` the trace file
- `nodeId` the `node_id` of this node, -1 gets substituted to parent module's index

---

Note: The AnsimMobility module processes only the `position_change` elements and it ignores the `start_time` attribute. It starts the move on the next segment immediately.

26.2.4 TurtleMobility

The TurtleMobility module can be parametrized by a script file containing LOGO-style movement commands in XML format. The content of the XML file should conform to the DTD in the `TurtleMobility.dtd` file in the source tree.

The file contains `movement` elements, each describing a trajectory. The `id` attribute of the `movement` element can be used to refer the movement from the ini file using the syntax:

```
**.mobility.turtleScript = xmldoc("turtle.xml", "movements//movement[@id='1']")
```

The motion of the node is composed of uniform linear segments. The `movement` elements may contain the the following commands as elements (names in parens are recognized attribute names):

- `repeat(n)` repeats its content n times, or indefinitely if the `n` attribute is omitted.
- `set(x,y,speed,angle,borderPolicy)` modifies the state of the node. `borderPolicy` can be `reflect`, `wrap`, `placerandomly` or `error`.

- `forward(d,t)` moves the node for `t` time or to the `d` distance with the current speed. If both `d` and `t` is given, then the current speed is ignored.
- `turn(angle)` increase the angle of the node by `angle` degrees.
- `moveto(x,y,t)` moves to point `(x,y)` in the given time. If t is not specified, it is computed from the current speed.
- `moveby(x,y,t)` moves by offset `(x,y)` in the given time. If t is not specified, it is computed from the current speed.
- `wait(t)` waits for the specified amount of time.

Attribute values must be given without physical units, distances are assumed to be given as meters, time intervals in seconds and speeds in meter per seconds. Attibutes can contain expressions that are evaluated each time the command is executed. The limits of the constraint area can be referenced as `$MINX`, `$MAXX`, `$MINY`, and `$MAXY`. Random number distibutions generate a new random number when evaluated, so the script can describe random as well as deterministic scenarios.

To illustrate the usage of the module, we show how some mobility models can be implemented as scripts.

RectangleMobility:

```
<movement>
    <set x="$MINX" y="$MINY" angle="0" speed="10"/>
    <repeat>
        <repeat n="2">
            <forward d="$MAXX-$MINX"/>
            <turn angle="90"/>
            <forward d="$MAXY-$MINY"/>
            <turn angle="90"/>
        </repeat>
    </repeat>
</movement>
```

Random Waypoint:

```
<movement>
    <repeat>
        <set speed="uniform(20,60)"/>
        <moveto x="uniform($MINX,$MAXX)" y="uniform($MINY,$MAXY)"/>
        <wait t="uniform(5,10)">
    </repeat>
</movement>
```

MassMobility:

```
<movement>
    <repeat>
        <set speed="uniform(10,20)"/>
        <turn angle="uniform(-30,30)"/>
        <forward t="uniform(0.1,1)"/>
    </repeat>
</movement>
```

CHAPTER

TWENTYSEVEN

MODELING POWER CONSUMPTION

27.1 Overview

Modeling power consumption becomes more and more important with the increasing number of embedded devices and the upcoming Internet of Things. Mobile personal medical devices, large scale wireless environment monitoring devices, electric vehicles, solar panels, low-power wireless sensors, etc. require paying special attention to power consumption. High-fidelity simulation of power consumption allows designing power-sensitive routing protocols, MAC protocols with power management features, etc., which in turn results in more energy efficient devices.

In order to help the modeling process, the INET power model is separated from other simulation models. This separation makes the power model extensible, and it also allows easy experimentation with alternative implementations. In a nutshell, the power model consists of the following components:

- energy consumption models
- energy generation models
- temporary energy storage models

The power model elements fall into two categories, abbreviated with `Ep` and `Cc` as part of their names:

- `Ep` models are simpler, and deal with energy and power quantities.
- `Cc` models are more realistic, and deal with charge, current, and voltage quantities.

The following sections provide a brief overview of the power model.

27.2 Energy Consumer Models

Energy consumer models describe the energy consumption of devices over time. For example, a transceiver consumes energy when it transmits or receives a signal, a CPU consumes energy when the network protocol forwards a packet, and a display consumes energy when it is turned on.

In INET, an energy consumer model is an OMNeT++ simple module that implements the energy consumption of software processes or hardware devices over time. Its main purpose is to provide the power or current consumption for the current simulation time. Most often energy consumers are included as submodules in the compound module of the hardware devices or software components.

INET provides only a few built-in energy consumer models:

- AlternatingEpEnergyGenerator is a trivial energy/power based statistical energy consumer model example.
- StateBasedEpEnergyConsumer is a transceiver energy consumer model based on the radio mode and transmission/reception states.

In order to simulate power consumption in a wireless network, the energy consumer model type must be configured for the transceivers. The following example demonstrates how to configure the power consumption parameters for a transceiver energy consumer model:

```
*.host[*].wlan[*].radio.energyConsumer.typename = "StateBasedEpEnergyConsumer"
*.host[*].wlan[*].radio.energyConsumer.sleepPowerConsumption = 0.1mW
*.host[*].wlan[*].radio.energyConsumer.receiverIdlePowerConsumption = 2mW
*.host[*].wlan[*].radio.energyConsumer.receiverBusyPowerConsumption = 5mW
*.host[*].wlan[*].radio.energyConsumer.receiverReceivingPowerConsumption = 10mW
*.host[*].wlan[*].radio.energyConsumer.transmitterIdlePowerConsumption = 2mW
*.host[*].wlan[*].radio.energyConsumer. \
   transmitterTransmittingPowerConsumption = 100mW # continue previous line
```

27.3 Energy Generator Models

Energy generator models describe the energy generation of devices over time. A solar panel, for example, produces energy based on time, the panel's location on the globe, its orientation towards the sun and the actual weather conditions. Energy generators connect to an energy storage that absorbs the generated energy.

In INET, an energy generator model is an OMNeT++ simple module implementing the energy generation of a hardware device using a physical phenomena over time. Its main purpose is to provide the power or current generation for the current simulation time. Most often energy generation models are included as submodules in network nodes.

INET provides only one trivial energy/power based statistical energy generator model called AlternatingEpEnergyGenerator. The following example shows how to configure its power generation parameters:

```
*.host[*].energyGenerator.typename = "AlternatingEpEnergyGenerator"
*.host[*].energyGenerator.energySinkModule = "^.energyStorage" # module ref.
*.host[*].energyGenerator.powerGeneration = 1mW
*.host[*].energyGenerator.sleepInterval = exponential(10s) # random intervals
*.host[*].energyGenerator.generationInterval = exponential(10s)
```

27.4 Energy Storage Models

Electronic devices which are not connected to external power source must contain some component to store energy. For example, an electrochemical battery in a mobile phone provides energy for its display, its CPU, and its communication devices. It might also absorb energy produced by a solar installed on its display, or by a portable charger plugged into the wall socket.

In INET, an energy storage model is an OMNeT++ simple module which models the physical phenomena that is used to store energy produced by generators and provide energy for consumers. Its main purpose is to compute the amount of available energy or charge at the current simulation time. It maintains a set of connected energy consumers and energy generators, their respective total power consumption and total power generation.

INET contains a few built-in energy storage models:

- IdealEpEnergyStorage is an idealistic model with infinite energy capacity and infinite power flow.
- SimpleEpEnergyStorage is a non-trivial model integrating the difference between the total consumed power and the total generated power over time.
- SimpleCcBattery is a more realistic charge/current based battery model using a charge independent ideal voltage source and internal resistance.

The following example shows how to configure a simple energy storage model:

```
*.host[*].energyStorage.typename = "SimpleEpEnergyStorage"
*.host[*].energyStorage.nominalCapacity = 0.05J # maximum capacity
*.host[*].energyStorage.initialCapacity = uniform(0J, this.nominalCapacity)
```

27.5 Energy Management Models

SimpleEpEnergyManagement

```
*.host[*].energyManagement.typename = "SimpleEpEnergyManagement"
*.host[*].energyManagement.nodeStartCapacity = 0.025J # start threshold
*.host[*].energyManagement.nodeShutdownCapacity = 0J # shutdown threshold
```

CHAPTER

TWENTYEIGHT

NETWORK EMULATION

28.1 Motivation

In INET, the word *emulation* is used in a broad sense to describe a system which is partially implemented in the real world and partially in simulation. Emulation is often used for testing and validating a simulation model with its real-world counterparts, or in a reverse scenario, during the development of a real-world protocol implementation or application, for testing it in a simulated environment. It may also be used out of necessity, because some part of the system only exists in the real world or only as a simulation model.

INET provides modules that act as bridges between the simulated and real domains, therefore it is possible to leave one part of the simulation unchanged, while simply extracting the other into the real world. Several setups are possible when one can take advantage of the emulation capabilities of INET:

- simulated node in a real network
- a simulated subnet in real network
- real-world node in simulated network
- simulated protocol in a real network node
- real application in a simulated network node
- etc.

Some example scenarios:

- Run a simulated component, such as an app or a routing protocol, on nodes of an actual ad-hoc network. This setup would allow testing the component's behavior under real-life conditions.
- Test the interoperability of a simulated protocol with its real-world counterparts.
- As a means of implementing hybrid simulation. The real network (or a single host OS) may contain several network emulator devices or simulations running in emulation mode. Such a setup provides a relatively easy way for connecting heterogenous simulators/emulators with each other, sparing the need for HLA or a custom interoperability solution.

28.2 Overview

For the simulation to act as a network emulator, two major problems need to be solved. On one hand, the simulation must run in real time, or the real clock must be configured according to the simulation time (synchronization). On the other hand, the simulation must be able to communicate with the real world (communication). This is achieved in INET as the following:

- Synchronization:
  - `RealTimeScheduler`: It is a socket-aware real-time scheduler class responsible for synchronization. Using this method, the simulation is run according to real time.
- Communication:

– The interface between the real (an interface of the OS) and the simulated parts of the model are represented by *Ext* modules, with names beginning with `Ext~` prefix in the simulation (`ExtLowerUdp`, `ExtUpperEthernetInterface`, etc.).

  Ext modules communicate both internally in the simulation and externally in the host OS. Packets sent to these modules in the simulation will be sent out on the host OS interface, and packets received by the host OS interface (or rather, the appropriate subset of them) will appear in the simulation as if received on an `Ext~` module.

  There are several possible ways to maintain the external communication:

  * File
  * Pipe
  * Socket
  * Shared memory
  * TUN/TAP interfaces
  * Message Passing Interface (MPI)

Note: It is probably needless to say, but the simulation must be fast enough to be able to keep up with real time. That is, its relative speed compared to real time (the simsec/sec value) must be >>1. (Under Qtenv, this can usually only be achieved in Express mode.)

28.3 Preparation

There are a few things that need to be arranged before you can successfully run simulations in network emulation mode.

First, network emulation is a separate *project feature* that needs to be enabled before it can be used. (Project features can be reviewed and changed in the *Project* | *Project Features...* dialog in the IDE.)

Also, in order to be able to send packets through raw sockets applications require special permissions. There are two ways to achieve this under Linux.

The suggested solution is to use setcap to set the application permissions:

```
$ sudo setcap cap_net_raw,cap_net_admin=eip /path/to/opp_run
$ sudo setcap cap_net_raw,cap_net_admin=eip /path/to/opp_run_dbg
$ sudo setcap cap_net_raw,cap_net_admin=eip /path/to/opp_run_release
```

This solution makes running the examples from the IDE possible. Alternatively, the application can be started with root privileges from command line:

```
$ sudo `inet_dbg -p -u Cmdenv`
```

Note: In any case, it's generally a bad idea to start the IDE as superuser. Doing so may silently change the file ownership for certain IDE configuration files, and it may prevent the IDE to start up for the normal user afterwards.

28.4 Configuring

Here we show one configuration example where the network nodes contain a ExtLowerEthernetInterface.

INET nodes such as StandardHost and Router can be configured to have ExtLowerEthernetInterface's. The simulation may contain several nodes with external interfaces, and one node may also have several external interfaces.

Note: This is one of the many possible setups. Using other components than ExtLowerEthernetInterface, nodes may be cut into simulated and real parts at any layer, and either the upper or the lower part may be real. See the Showcases for demonstration of some of these use cases.

A network node can be configured to have an external interface in the following way:

```
**.host1.numEthInterfaces = 1
**.host1.eth[0].typename = "ExtLowerEthernetInterface"
```

Also, the simulation must be configured to run under control the of the appropriate real-time scheduler class:

```
scheduler-class = "inet::RealTimeScheduler"
```

ExtLowerEthernetInterface has two important parameters which need to be configured. The `device` parameter should be set to the name of the real (or virtual) interface on the host OS. The `namespace` parameter can be set to utilize the network namespace functionality of Linux operating systems.

An example configuration:

```
**.numEthInterfaces = 1
**.eth[0].device = "veth0" # or "eth0" for example
**.eth[0].namespace = "host0" # optional
**.eth[0].mtu = 1500B
```

Let us examine the paths outgoing and incoming packets take, and the necessary configuration requirements to make them work. We assume IPv4 as network layer protocol, but the picture does not change much with other protocols. We assume the external interface is named `eth[0]`.

28.4.1 Outgoing path

The network layer of the simulated node routes datagrams to its `eth[0]` external interface.

For that to happen, the routing table needs to contain an entry where the interface is set to `eth[0]`. Such entries are not created automatically, one needs to add them to the routing table explicitly, e.g. by using an Ipv4NetworkConfigurator and an appropriate XML file.

Another point is that if the packet comes from a local app (and from another simulated node), it needs to have a source IP address assigned. There are two ways for that to happen. If the sending app specified a source IP address, that will be used. Otherwise, the IP address of the `eth[0]` interface will be used, but for that, the interface needs to have an IP address at all. The MAC and IP address of external interfaces are automatically copied between the real and simulated counterparts.

Once in `eth[0]`, the datagram is serialized. Serialization is a built-in feature of INET packets. (Packets, or rather, packet chunks have multiple alternative representations, i.e. C++ object and serialized form, and conversion between them is transparent.)

The result of serialization is a byte array, which is written into a raw socket with a `sendto` system call.

The packet will then travel normally in the real network to the destination address.

28.4.2 Incoming path

First of all, packets intended to be received by the simulation need to find their way to the correct interface of the host that runs the simulation. For that, IP addresses of simulated hosts must be routable in the real network, and routed to the selected interface of the host OS. (On Linux, for example, this can be achieved by adding static routes with the command.)

As packets are received by the interface of the host OS, they are handed over to the simulation. The packets are received from the raw socket with a `recv` system call. After deserialization they pop out of `eth[0]` and they are sent up to the network layer. The packets are routed to the simulated destination host in the normal way.

CHAPTER

TWENTYNINE

SCENARIO SCRIPTING

29.1 Overview

The INET Framework contains scripting support to help the user express scenarios that cannot be adequately described using static configuration. You can schedule actions to be carried out at specified simulation times, for example changing a parameter value, changing the bit error rate of a connection, removing or adding connections, removing or adding routes in a routing table, shutting down or crashing routers, etc. The aim is usually to observe transient behaviour caused by the changes.

INET supports the following built-in actions:

- Create or delete module
- Create or delete connection
- Set module or channel parameter
- Initiate lifecycle operation (startup, shutdown, crash) on a network node or part of it

29.2 ScenarioManager

The ScenarioManager module type is for setting up and controlling simulation experiments. In typical usage, it has only one instance in the network:

```
network Test {
    submodules:
        scenarioManager: ScenarioManager;
        ...
}
```

ScenarioManager executes a script specified in XML. It has a few built-in commands, while other commands are dispatched (in C++) to be carried out by other simple modules.

An example script:

```
<scenario>
    <set-param t="10" module="host[1].mobility" par="speed" value="5"/>
    <set-param t="20" module="host[1].mobility" par="speed" value="30"/>
    <at t="50">
        <set-param module="host[2].mobility" par="speed" value="10"/>
        <set-param module="host[3].mobility" par="speed" value="10"/>
        <connect src-module="host[2]" src-gate="ppp[0]"
                 dest-module="host[1]" dest-gate="ppp[0]"
                 channel-type="ned.DatarateChannel">
            <param name="datarate" value="10Mbps" />
            <param name="delay" value="0.1us" />
        </connect>
    </at>
```

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```
    <at t="60">
        <disconnect src-module="host[2]" src-gate="ppp[0]" />
    </at>
</scenario>
```

The above script probably does not need much explanation.

The built-in commands of ScenarioManager are: <connect>, <disconnect>, <create-module>, <delete-module>, <initiate>, <shutdown>, <startup>, <crash>, <set-param>, <set-channel-attr>, <at>.

All commands have a t attribute which carries the simulation time at which the command has to be carried out. You can group several commands to be carried out at the same simulation time using <at>, and then only the <at> command needs to have a t attribute.

More information can be found in the ScenarioManager documentation.

The script is usually placed in a separate file, and specified like this:

```
*.scenarioManager.script = xmldoc("scenario.xml")
```

Short scripts can also be written inline:

```
*.scenarioManager.script = xml("<x><shutdown t='2s' module='Router2'/></x>")
```

CHAPTER

THIRTY

MODELING NODE FAILURES

30.1 Overview

Simulation is often used to study the effects of unexpected events like a router crash on the network. In order to accommodate such scenarios, INET supports *lifecycle modeling* of network nodes. The up/down status of a node is changed via lifecycle operations.

INET supports the following lifecycle operations:

- *Startup* represents the process of booting up or starting a network node after a shutdown or crash operation.
- *Shutdown* represents the process of orderly shutting down a network node.
- *Crash* represents the process of crashing a network node. The difference between *crash* and *shutdown* is that for a crash, the network node will not do a graceful shutdown (e.g. routing protocols will not have a chance of notifying peers about broken routes).

In a real-life router or other network node, a crash or shutdown and subsequent restart affects all parts of the system. All non-persistent information is lost. Protocol states are reset, various tables are cleared, connections are broken or torn down, applications restart, and so on.

Mimicking this behavior in simulation does not come for free, it needs to be explicitly programmed into each affected component. Here are some examples how INET components react to a *crash* lifecycle event:

- Tcp forgets all open connections and sockets
- Ipv4 clears the fragmentation reassembly buffers and pending packets
- Ipv4RoutingTable clears the route table
- EtherMac and other MAC protocols clear their queues and reset their state associated with the current transmission(s)
- Ospfv2 clears its full state
- UdpBasicApp, TcpSessionApp and other applications reset their state and stop/restart their timers
- EtherSwitch, AccessPoint, and other L2 bridging devices clear their MAC address tables

While down, network interfaces, and components in general, ignore (discard) messages sent to them.

Lifecycle operations are currently instanteneous, i.e. they complete in zero simulation time. The underlying framework would allow for modeling them as processes that take place in some finite (nonzero) simulation time, but this possibility is currently not in use.

It also is possible to simulate a crash or shutdown of part of a node (certain protocols or interfaces only). Such scenarios would correspond to e.g. the crash of an OSPF daemon on a real OS.

Some energy-related INET components trigger node shutdown or crash under certain conditions. For example, a node will crash when it runs out of power (e.g. its battery depletes); see the chapter on power consumption modeling *Modeling Power Consumption* for details.

In the following sections we outline the INET components that participate in lifecycle modeling, and show a usage example.

30.2 NodeStatus

Node models contain a NodeStatus module that keeps track of the status of the node (up, down, etc.) for other modules, and also displays it in the GUI as a small overlay icon.

The NodeStatus module is declared conditionally (so that it is only created in simulations that need it), like this:

```
status: NodeStatus if hasStatus;
```

If lifecycle modeling is required, the following line must be added to the ini file to ensure that nodes have status modules:

```
**.hasStatus = true
```

30.3 Scripting

Lifecycle operations can be triggered from C++ code, or from scripts. INET supports scripting via the ScenarioManager NED type, described in chapter *Scenario Scripting*. Here is an example script that shuts down a router at simulation time 2s, and starts it up a again at time 8s:

```
<scenario>
  <initiate t="2s" module="Router2" operation="shutdown"/>
  <initiate t="8s" module="Router2" operation="startup"/>
</scenario>
```

The `module` attribute should point to the module (host, router, network interface, protocol, etc.) to be operated on. The `operation` attribute should contain the operation to perform: `"shutdown"`, `"crash"`, or `"startup"`. `t` is the simulation time the operation should be initiated at.

An alternative, shorter form is to use `<shutdown>` / `<crash>` / `<startup>` elements instead of the `operation` attribute:

```
<scenario>
  <shutdown t="2s" module="Router2"/>
  <startup  t="8s" module="Router2"/>
</scenario>
```

CHAPTER

THIRTYONE

COLLECTING RESULTS

The following sections introduce the INET specific concepts and features for collecting simulation results. For more information in general on collecting statistics please refer to the OMNeT++ manual.

31.1 Recording Statistics

Most INET modules are already equipped with the collection of various statistics. You can find these as *@statistic* properties in the corresponding NED files. By default, many of them are already configured to be automatically recorded as either scalars, vectors, or histograms depending on the typical usefulness of the statistic. Note that it's possible to change the default recording mode from INI files as described in the OMNeT++ manual.

If the default statistics, provided by the INET modules, are not sufficient, then you can derive new modules using only NED files, and add new statistics to them based on the signals already emitted by the module. The emitted signals can also be found as @signal properties declared in the corresponding NED files.

If even declaring new statistics isn't sufficient, then you can also derive new C++ classes from the module implementations, and add new signals and/or add new statistic collection code to them. This is the most cumbersome way to collect new results, but it's also the most expressive allowing to collect any kind of statistic.

31.2 Measuring along Packet Flows

By default, INET statistics are only capable of collecting results based on the data that individual protocol modules and applications can access. Each module collects statistics independently of the rest of the network often rendering the statistics less useful in complex scenarios. For example, a TCP protocol module that communicates with multiple other TCP modules cannot distinguish between the packets based on the path they took. To overcome this issue, INET introduces the notion of packet flows.

A packet flow is a logical classification of packets, identified by its name, over the whole network and over the duration of the whole simulation. Basically, at any given moment any packet that is present anywhere in the network can be part of any number of packet flows. Packets may enter a packet flow and leave it multiple times. Different packet flows can overlap both in time and also along the network topology. Note that a packet flow doesn't necessarily have a single entry and a single exit point.

A packet flow is usually defined by active modules that classify certain packets (e.g. matching a filter) to be entering the flow, and similarly other modules that decide when packets leave the flow. Both kind of modules are inserted into the network for this specific purpose usually at the network interface level. While a packet is being part of any number of packet flows, certain INET modules (e.g. queues) are going to automatically record certain events that happen with the packets (e.g. queueing).

So far, the notion of packet flows were introduced on the packet level. That is at any given time a packet is either completely part of a packet flow or not. In fact, this is a simplification for easier understanding. This approach is clearly not sufficient in the general case, because packets can be fragmented and aggregated throughout the network, and they can traverse many different paths. Therefore the packet flow membership is actually specified on a per bit basis. The implementation takes care of efficiently representing this data, so the coherent parts of a packet that belongs to the same packet flow is marked together.

Using the packet flow mechanism, one can easily measure the timing of various things that happen to a packet (or to a part of it). The following quantities are automatically measured (if requested) along packet flows:

- total elapsed time measured from entering the packet flow
- total time spent in queues (e.g. transmission queue)
- total delay spent in various non-queue modules (e.g. interframe gap)
- total time spent in various packet processing modules (e.g. packet server)
- total transmission time of transmitters
- total propagation time spent on the transmission medium

The collected timing data is attached to coherent regions of the packets while the packets are in the packet flow. The actual measurement, that is collecting the statistical results is usually done when the packets leave the packet flow.

If the timing statistics are not sufficient, it's also possible to collect all packet events that happens to packets in the packet flow. The following packet events can be automatically collected along packet flows:

- packet is enqueued in a packet queue (e.g. transmission queue)
- packet is delayed (e.g. interframe gap)
- packet is processed (e.g. packet server)
- packet is transmitted by a wired or wireless transmitter
- packet is propagated on a wired or wireless transmission medium

The collected packet event data structure is also attached to coherent regions of the packet while the packets are in the packet flow. To actually make a measurement, a new measurement module must be implemented which processes the collected data.

In order to configure one of the above packet flow measurements, you can use the following modules:

- TimingMeasurementStarter: classifies packets to enter packet flows and starts timing measurements or packet event collection.
- TimingMeasurementMaker: completes timing measurements, collects statistics and makes packets leave the packet flow.
- MeasurementLayer: can be added to network nodes and network interfaces for optional packet flow measurements.

31.3 Recording PCAP Traces

The easiest way to understand the behavior of a communication network on the network level is to look at the actual packets that are exchanged. INET supports recording such packet traces in the widely used PCAP and its more recent sibling the PCAPng file formats. These file formats allow analyzing the network traffic using the well-known Wireshark packet analyizer.

All network nodes and network interfaces support the recording of incoming and outgoing traffic into PCAP files via optional PcapRecorder modules. By default, this module records all packets emitted with configured signals from its parent module. For example, a recorder module put in the network interface module records all traffic specific to that network interface, and similarly a recorder put in the network node records all traffic from the given node. It's also possible to put a PCAP recorder module on the network level to produce a PCAP file that contains all network traffic. If the traffic of more than one network interface is recorded into a signle file, then the newer PCAPng file format must be used to also record the data of the corresponding network interfaces.

Recording PCAP traces also supports using packet filters, which in turn allows one to produce multiple files for the same network interface containing different kind of traffic.

31.4 Recording Routing Tables

Understanding the behavior of routing protocols, especially with respect to the dynamic state of all routing tables, in a complex communication network is a difficult thing to do. In order to ease this task, INET provides a special RoutingTableRecorder module which is capable of recording all network interface data along with all routes in all routing tables into a single log file.

The log file uses a simple text based format. It contains one line for each network interface added, changed, or deleted, and it also contains one line for each route added, changed, or deleted in all network nodes. The resulting log file can be used, for example, to verify that certain changes don't affect the way routes are discovered in the network.

CHAPTER

THIRTYTWO

VISUALIZATION

32.1 Overview

The INET Framework is able to visualize a wide range of events and conditions in the network: packet drops, data link connectivity, wireless signal path loss, transport connections, routing table routes, and many more. Visualization is implemented as a collection of configurable INET modules that can be added to simulations at will.

32.2 Visualizing Network Communication

32.2.1 Visualizing Packet Drops

Several network problems manifest themselves as excessive packet drops, for example poor connectivity, congestion, or misconfiguration. Visualizing packet drops helps identifying such problems in simulations, thereby reducing time spent on debugging and analysis. Poor connectivity in a wireless network can cause senders to drop unacknowledged packets after the retry limit is exceeded. Congestion can cause queues to overflow in a bottleneck router, again resulting in packet drops.

Packet drops can be visualized by including a PacketDropVisualizer module in the simulation. The PacketDropVisualizer module indicates packet drops by displaying an animation effect at the node where the packet drop occurs. In the animation, a packet icon gets thrown out from the node icon, and fades away.

The visualization of packet drops can be enabled with the visualizer's `displayPacketDrops` parameter. By default, packet drops at all nodes are visualized. This selection can be narrowed with the `nodeFilter`, `interfaceFilter` and `packetFilter` parameters.

One can click on the packet drop icon to display information about the packet drop in the inspector panel.

Packets are dropped for the following reasons:

- queue overflow
- retry limit exceeded
- unroutable packet
- network address resolution failed
- interface down

32.2.2 Visualizing Transport Path Activity

With INET simulations, it is often useful to be able to visualize network traffic. INET provides several visualizers for this task, operating at various levels of the network stack. One of such visualizers is TransportRouteVisualizer that provides graphical feedback about transport layer traffic.

TransportRouteVisualizer visualizes traffic that passes through the transport layers of two endpoints. Adding an IntegratedVisualizer is also an option, because it also contains a TransportRouteVisualizer. Transport path activity visualization is disabled by default, it can be enabled by setting the visualizer's `displayRoutes` parameter to true.

TransportRouteVisualizer observes packets that pass through the transport layer, i.e. carry data from/to higher layers.

The activity between two nodes is represented visually by a polyline arrow which points from the source node to the destination node. TransportRouteVisualizer follows packets throughout their path so that the polyline goes through all nodes which are the part of the path of packets. The arrow appears after the first packet has been received, then gradually fades out unless it is reinforced by further packets. Color, fading time and other graphical properties can be changed with parameters of the visualizer.

By default, all packets and nodes are considered for the visualization. This selection can be narrowed with the visualizer's packetFilter and nodeFilter parameters.

32.2.3 Visualizing Network Path Activity

Network layer traffic can be visualized by including a NetworkRouteVisualizer module in the simulation. Adding an IntegratedVisualizer module is also an option, because it also contains a NetworkRouteVisualizer module. Network path activity visualization is disabled by default, it can be enabled by setting the visualizer's `displayRoutes` parameter to true.

NetworkRouteVisualizer currently observes packets that pass through the network layer (i.e. carry data from/to higher layers), but not those that are internal to the operation of the network layer protocol. That is, packets such as ARP, although potentially useful, will not trigger the visualization.

The activity between two nodes is represented visually by a polyline arrow which points from the source node to the destination node. NetworkRouteVisualizer follows packet throughout its path so the polyline goes through all nodes that are part of the packet's path. The arrow appears after the first packet has been received, then gradually fades out unless it is reinforced by further packets. Color, fading time and other graphical properties can be changed with parameters of the visualizer.

By default, all packets and nodes are considered for the visualization. This selection can be narrowed with the visualizer's packetFilter and nodeFilter parameters.

32.2.4 Visualizing Data Link Activity

Data link activity (layer 2 traffic) can be visualized by adding a DataLinkVisualizer module to the simulation. Adding an IntegratedVisualizer module is also an option, because it includes a DataLinkVisualizer module. Data link visualization is disabled by default, it can be enabled by setting the visualizer's displayLinks parameter to true.

DataLinkVisualizer currently observes packets that pass through the data link layer (i.e. carry data from/to higher layers), but not those that are internal to the operation of the data link layer protocol. That is, frames such as ACK, RTS/CTS, Beacon or Authentication/Association frames of IEEE 802.11, although potentially useful, will not trigger the visualization. Visualizing such frames may be implemented in future INET revisions.

The activity between two nodes is represented visually by an arrow that points from the sender node to the receiver node. The arrow appears after the first packet has been received, then gradually fades out unless it is refreshed by further packets. The style, color, fading time and other graphical properties can be changed with parameters of the visualizer.

By default, all packets, interfaces and nodes are considered for the visualization. This selection can be narrowed to certain packets and/or nodes with the visualizer's `packetFilter`, `interfaceFilter`, and `nodeFilter` parameters.

32.2.5 Visualizing Physical Link Activity

Physical link activity can be visualized by including a PhysicalLinkVisualizer module in the simulation. Adding an IntegratedVisualizer module is also an option, because it also contains a PhysicalLinkVisualizer module. Physical link activity visualization is disabled by default, it can be enabled by setting the visualizer's `displayLinks` parameter to true.

PhysicalLinkVisualizer observes frames that pass through the physical layer, i.e. are received correctly.

The activity between two nodes is represented visually by a dotted arrow which points from the sender node to the receiver node. The arrow appears after the first frame has been received, then gradually fades out unless it is refreshed by further frames. Color, fading time and other graphical properties can be changed with parameters of the visualizer.

By default, all packets, interfaces and nodes are considered for the visualization. This selection can be narrowed with the visualizer's `packetFilter`, `interfaceFilter`, and `nodeFilter` parameters.

32.2.6 Visualizing Routing Tables

In a complex network topology, it is difficult to see how a packet would be routed because the relevant data is scattered among network nodes and hidden in their routing tables. INET contains support for visualization of routing tables, and can display routing information graphically in a concise way. Using visualization, it is often possible to understand routing in a simulation without looking into individual routing tables. The visualization currently supports IPv4.

The RoutingTableVisualizer module (included in the network as part of IntegratedVisualizer) is responsible for visualizing routing table entries.

The visualizer basically annotates network links with labeled arrows that connect source nodes to next hop nodes. The module visualizes those routing table entries that participate in the routing of a given set of destination addresses, by default the addresses of all interfaces of all nodes in the network. That is, it selects the best (longest prefix) matching routes for all destination addresses from each routing table, and shows them as arrows that point to the next hop. Note that one arrow might need to represent several routing entries, for example when distinct prefixes are routed towards the same next hop.

Routing table entries are represented visually by solid arrows. An arrow going from a source node represents a routing table entry in the source node's routing table. The endpoint node of the arrow is the next hop in the visualized routing table entry. By default, the routing entry is displayed on the arrows in following format:

```
destination/mask -> gateway (interface)
```

The format can be changed by setting the visualizer's `labelFormat` parameter.

Filtering is also possible. The `nodeFilter` parameter controls which nodes' routing tables should be visualized (by default, all nodes), and the `destinationFilter` parameter selects the set of destination nodes to consider (again, by default all nodes.)

The visualizer reacts to changes. For example, when a routing protocol changes a routing entry, or an IP address gets assigned to an interface by DHCP, the visualizer automatically updates the visualizations according to the specified filters. This is very useful e.g. for the simulation of mobile ad-hoc networks.

32.2.7 Displaying IP Addresses and Other Interface Information

In the simulation of complex networks, it is often useful to be able to display node IP addresses, interface names, etc. above the node icons or on the links. For example, when automatic address assignment is used in a hierarchical network (e.g. using Ipv4NetworkConfigurator), visual inspection can help to verify that the result matches the expectations. While it is true that addresses and other interface data can also be accessed in the GUI by diving into the interface tables of each node, that is tedious, and unsuitable for getting an overview.

The InterfaceTableVisualizer module (included in the network as part of IntegratedVisualizer) displays data about network nodes' interfaces. (Interfaces are contained in interface tables, hence the name.) By default, the visualization is turned off. When it is enabled using the `displayInterfaceTables` parameter, the default is that interface names, IP addresses and netmask length are displayed, above the nodes (for wireless interfaces) and on the links (for wired interfaces). By clicking on an interface label, details are displayed in the inspector panel.

The visualizer has several configuration parameters. The `format` parameter specifies what information is displayed about interfaces. It takes a format string, which can contain the following directives:

- %N: interface name
- %4: IPv4 address
- %6: IPv6 address
- %n: network address. This is either the IPv4 or the IPv6 address
- %l: netmask length
- %M: MAC address
- %: conditional newline for wired interfaces. The " needs to be escaped with another ", i.e. '%\'
- %i and %s: the info() and str() functions for the interfaceEntry class, respectively

The default format string is `"%N %\\%n/%l"`, i.e. interface name, IP address and netmask length.

The set of visualized interfaces can be selected with the configurator's `nodeFilter` and `interfaceFilter` parameters. By default, all interfaces of all nodes are visualized, except for loopback addresses (the default for the `interfaceFilter` parameter is `"not lo\"`.)

It is possible to display the labels for wired interfaces above the node icons, instead of on the links. This can be done by setting the `displayWiredInterfacesAtConnections` parameter to false.

There are also several parameters for styling, such as color and font selection.

32.2.8 Visualizing IEEE 802.11 Network Membership

When simulating wifi networks that overlap in space, it is difficult to see which node is a member of which network. The membership may even change over time. It would be useful to be able to display e.g. the SSID above node icons.

IEEE 802.11 network membership can be visualized by including a Ieee80211Visualizer module in the simulation. Adding an IntegratedVisualizer is also an option, because it also contains a Ieee80211Visualizer. Displaying network membership is disabled by default, it can be enabled by setting the visualizer's `displayAssociations` parameter to true.

The Ieee80211Visualizer displays an icon and the SSID above network nodes which are part of a wifi network. The icons are color-coded according to the SSID. The icon, colors, and other visual properties can be configured via parameters of the visualizer.

The visualizer's `nodeFilter` parameter selects which nodes' memberships are visualized. The `interfaceFilter` parameter selects which interfaces are considered in the visualization. By default, all interfaces of all nodes are considered.

32.2.9 Visualizing Transport Connections

In a large network with a complex topology, there might be many transport layer applications and many nodes communicating. In such a case, it might be difficult to see which nodes communicate with which, or if there is any communication at all. Transport connection visualization makes it easy to get information about the active transport connections in the network at a glance. Visualization makes it easy to identify connections by their two endpoints, and to tell different connections apart. It also gives a quick overview about the number of connections in individual nodes and the whole network.

The TransportConnectionVisualizer module (also part of IntegratedVisualizer) displays color-coded icons above the two endpoints of an active, established transport layer level connection. The icons will appear when the connection is established, and disappear when it is closed. Naturally, there can be multiple connections open at a node, thus there can be multiple icons. Icons have the same color at both ends of the connection. In addition to colors, letter codes (A, B, AA, ...) may also be displayed to help in identifying connections. Note that this visualizer does not display the paths the packets take. If you are interested in that, take a look at TransportRouteVisualizer, covered in section *Visualizing Transport Path Activity*.

The visualization is turned off by default, it can be turned on by setting the `displayTransportConnections` parameter of the visualizer to true.

It is possible to filter the connections being visualized. By default, all connections are included. Filtering by hosts and port numbers can be achieved by setting the `sourcePortFilter`, `destinationPortFilter`, `sourceNodeFilter` and `destinationNodeFilter` parameters.

The icon, colors and other visual properties can be configured by setting the visualizer's parameters.

32.3 Visualizing The Infrastructure

32.3.1 Visualizing the Physical Environment

The physical environment has a profound effect on the communication of wireless devices. For example, physical objects like walls inside buildings constraint mobility. They also obstruct radio signals often resulting in packet loss. It's difficult to make sense of the simulation without actually seeing where physical objects are.

The visualization of physical objects present in the physical environment is essential.

The PhysicalEnvironmentVisualizer (also part of IntegratedVisualizer) is responsible for displaying the physical objects. The objects themselves are provided by the PhysicalEnvironment module; their geometry, physical and visual properties are defined in the XML configuration of the PhysicalEnvironment module.

The two-dimensional projection of physical objects is determined by the SceneCanvasVisualizer module. (This is because the projection is also needed by other visualizers, for example MobilityVisualizer.) The default view is top view (z axis), but you can also configure side view (x and y axes), or isometric or ortographic projection.

The visualizer also supports OpenGL-based 3D rendering using the OpenSceneGraph (OSG) library. If the OMNeT++ installation has been compiled with OSG support, you can switch to 3D view using the Qtenv toolbar.

32.3.2 Visualizing Node Mobility

In INET simulations, the movement of mobile nodes is often as important as the communication among them. However, as mobile nodes roam, it is often difficult to visually follow their movement. INET provides a visualizer that not only makes visually tracking mobile nodes easier, but also indicates other properties like speed and direction.

Node mobility of nodes can be visualized by MobilityVisualizer module (included in the network as part of IntegratedVisualizer). By default, mobility visualization is enabled, it can be disabled by setting `displayMovements` parameter to false.

By default, all mobilities are considered for the visualization. This selection can be narrowed with the visualizer's `moduleFilter` parameter.

The visualizer has several important features:

- Movement Trail: It displays a line along the recent path of movements. The trail gradually fades out as time passes. Color, trail length and other graphical properties can be changed with parameters of the visualizer.
- Velocity Vector: Velocity is represented visually by an arrow. Its starting point is the node, and its direction coincides with the movement's direction. The arrow's length is proportional to the node's speed.
- Orientation Arc: Node orientation is represented by an arc whose size is specified by the `orientationArcSize` parameter. This value is the relative size of the arc compared to a full circle. The arc's default value is 0.25, i.e. a quarter of a circle.

These features are disabled by default; they can be enabled by setting the visualizer's `displayMovementTrails`, `displayVelocities` and `displayOrientations` parameters to true.

CHAPTER

THIRTYTHREE

INSTRUMENT FIGURES

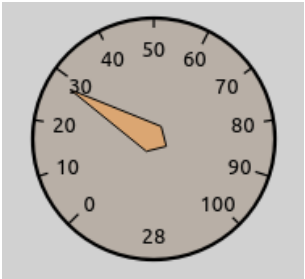
33.1 Overview

In complex simulations, there are usually several statistics that are vital for understanding what is happening inside the network. Although statistics can also be found and read in Qtenv's object inspector panel, it is often more convenient to directly display them on the top-level canvas in a graphical form. INET supports such visualization in the form of inspector figures that display various gauges and meters. This chapter covers the usage of instrument figures.

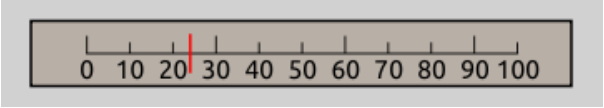
33.2 Instrument Types

Some of the instrument figure types available in INET are the following:

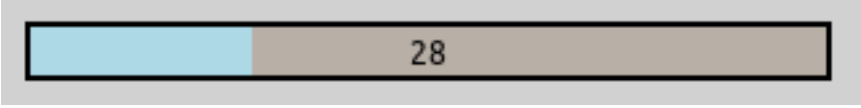
- *gauge:* A circular gauge similar to a speedometer or pressure indicator.



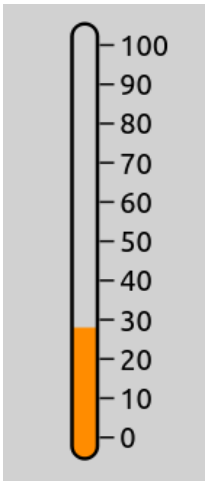
- *linearGauge:* A horizontal linear gauge similar to a VU meter.

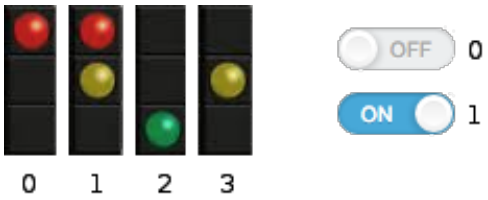


- *progressMeter:* A horizontal progress bar.

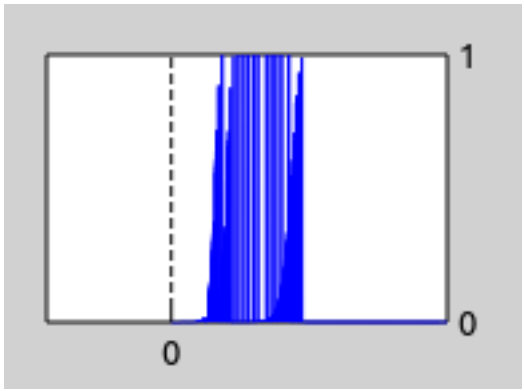


- *counter:* An integer counter.
- *thermometer:* A vertical meter visually similar to a real-life thermometer.
- *indexedImage:* A figure that displays one of several images: the first image for the value 0, the second image for the value of 1, and so on.





- *plot:* An XY chart that plots a statistic in the function of time.



33.3 Using Instrument Figures

Instrument figures visualize statistics derived from signals emitted by modules in the network. This statistic is declared in the NED file, with the `@statistic` property. The property's `source` attribute is an expression that specifies which signals to use from which modules, and the mathematical operations on it, to derive the statistic. The `record` attribute specifies where the values of the statistic is recorded into. In the case of instrument figures, this is set to `figure`, i.e. `record=figure`. The `targetFigure` attribute selects which figure should display the statistic.

The instrument figure itself is specified in the NED file with the `@figure` property. The property's `type` attribute selects the type of the instrument figure (`gauge`, `thermometer`, etc.), and the property's index (i.e. the figure name) should match the name given in the statistic's `targetFigure` attribute.

Here is an example NED file:

```
@statistic[numRcvdPk](source=count(client.app[0].rcvdPk); record=figure;␣
↪targetFigure=counter);
@figure[numRcvdPkCounter](type=counter; pos=413,327; label="Packets received";␣
↪decimalPlaces=4);
```

This creates a figure named `numRcvdPkCounter`, which displays a counter. The statistic `numRcvdPk` counts the packets received by the `client` host's first application, and records it in the `numRcvdPkCounter` figure.

33.4 Instrument Figure Attributes

Instrument figures have various attributes that customize their position, size, appearance, label text and font, minimum and maximum values, and so on. The following list shows the attributes recognized by the various figure types (a similar list can be produced by running INET with the `-h figures` command-line option):

counter: `type`, `visible`, `zIndex`, `tooltip`, `tags`, `transform`, `backgroundColor`, `decimalPlaces`, `digitBackgroundColor`, `digitBorderColor`, `digitFont`, `digitColor`, `label`, `labelFont`, `labelColor`, `initialValue`, `pos`, `anchor`, `labelOffset`

gauge: `type`, `visible`, `zIndex`, `tooltip`, `tags`, `transform`, `backgroundColor`, `needleColor`, `label`, `labelFont`, `labelColor`, `minValue`, `maxValue`, `tickSize`, `colorStrip`, `initialValue`, `pos`, `size`, `anchor`, `bounds`, `labelOffset`

indexedImage: `type`, `visible`, `zIndex`, `tooltip`, `tags`, `transform`, `images`, `tintAmount`, `tintColor`, `opacity`, `interpolation`, `label`, `labelFont`, `labelColor`, `labelOffset`, `initialValue`, `pos`, `size`, `anchor`, `bounds`

indicatorLabel: `type`, `visible`, `zIndex`, `tooltip`, `tags`, `transform`, `pos`, `anchor`, `text`, `font`, `color`, `opacity`, `halo`, `textFormat`, `initialValue`

indicatorText: `type`, `visible`, `zIndex`, `tooltip`, `tags`, `transform`, `pos`, `anchor`, `text`, `font`, `color`, `opacity`, `halo`, `textFormat`, `initialValue`

linearGauge: `type`, `visible`, `zIndex`, `tooltip`, `tags`, `transform`, `backgroundColor`, `needleColor`, `label`, `labelFont`, `labelColor`, `minValue`, `maxValue`, `tickSize`, `cornerRadius`, `initialValue`, `pos`, `size`, `anchor`, `bounds`, `labelOffset`

plot: `type`, `visible`, `zIndex`, `tooltip`, `tags`, `transform`, `valueTickSize`, `timeWindow`, `timeTickSize`, `lineColor`, `minValue`, `maxValue`, `backgroundColor`, `label`, `labelOffset`, `labelColor`, `labelFont`, `numberSizeFactor`, `pos`, `size`, `anchor`, `bounds`

progressMeter: `type`, `visible`, `zIndex`, `tooltip`, `tags`, `transform`, `backgroundColor`, `stripColor`, `cornerRadius`, `borderWidth`, `minValue`, `maxValue`, `text`, `textFont`, `textColor`, `label`, `labelOffset`, `labelFont`, `labelColor`, `initialValue`, `pos`, `size`, `anchor`, `bounds`

thermometer: `type`, `visible`, `zIndex`, `tooltip`, `tags`, `transform`, `mercuryColor`, `label`, `labelFont`, `labelColor`, `minValue`, `maxValue`, `tickSize`, `initialValue`, `pos`, `size`, `anchor`, `bounds`, `labelOffset`

CHAPTER

THIRTYFOUR

APPENDIX: AUTHOR'S GUIDE

34.1 Overview

This chapter is intended for authors and contributors of this *INET User's Guide*, and covers the guidelines for deciding what type of content is appropriate for this *Guide* and what is not.

The main guiding principle is to avoid redundancy and duplication of information with other pieces of documentation, namely:

- Standards documents (RFCs, IEEE specifications, etc.) that describe protocols that INET modules implement;
- *INET Developer's Guide*, which is intended as a guide for anyone wishing to understand or modify the operation of INET's components at C++ level;
- *INET Framework Reference*, directly generated from NED and MSG comments by OMNeT++ documentation generator;
- Showcases, tutorials and simulation examples (`showcases/`, `tutorials/` and `examples/` folders in the INET project)

Why is duplication to be avoided? Multiple reasons:

- It is a waste of our reader's time they have to skip information they have already seen elsewhere
- The text can easily get out of date as the INET Framework evolves
- It is extra effort for maintainers to keep all copies up to date

34.2 Guidelines

34.2.1 Do Not Repeat the Standard

When describing a module that implements protocol X, do not go into lengths explaining what protocol X does and how it works, because that is appropriately (and usually, much better) explained in the specification or books on protocol X. It is OK to summarize the protocol's goal and principles in short paragraph though.

In particular, do not describe the *format of the protocol messages*. It surely looks nice and takes up a lot of space, but the same information can probably be found in a myriad places all over the internet.

34.2.2 Do Not Repeat NED

Things like module parameters, gate names, emitted signals and collected statistics are appropriately and formally part of the NED definitions, and there is no need to duplicate that information in this *Guide*.

Detailed information on the module, such as *usage details* and the list of *implemented standards* should be covered in the module's NED documentation, not in this *Guide*.

34.2.3 No C++

Any content which only makes sense on C++ level should go to the *Developer's Guide*, and has no place in this *Guide*.

34.2.4 Keep Examples Short

When giving examples about usage, keep them concise and to the point. Giving ini or NED file fragments of a few lines length is preferable to complete working examples.

Complete examples should be written up as showcases. A working simulation without much commentary should go under `examples`. A practical, potentially multi-step guide to using a nontrivial feature should be written up as a tutorial.

34.2.5 No Reference to Simulation Examples

Do not refer to concrete example simulations, showcases or tutorials in the text, because they might get renamed, moved, merged or deleted, and when they do, no one will think about updating the reference in the *Users Guide*.

34.2.6 What then?

Concentrate on giving a "big picture" of the models: what it is generally capable of, how the parts fit together, etc. Give just enough information that after a quick read, users can "bootstrap" into putting together their own simulations with the model. If they have questions afterwards, they will/should refer to the NED documentation (INET Reference), or if that's not enough, delve into the C++ code to find the answers.

CHAPTER

THIRTYFIVE

HISTORY

35.1 IPSuite to INET Framework (2000-2006)

The predecessor of the INET framework was written by Klaus Wehrle, Jochen Reber, Dirk Holzhausen, Volker Boehm, Verena Kahmann, Ulrich Kaage and others at the University of Karlsruhe during 2000-2001, under the name IPSuite.

The MPLS, LDP and RSVP-TE models were built as an add-on to IPSuite during 2003 by Xuan Thang Nguyen (Xuan.T.Nguyen@uts.edu.au) and other students at the University of Technology, Sydney under supervision of Dr Robin Brown. The package consisted of around 10,000 LOCs, and was published at http://charlie.it.uts.edu.au/ tkaphan/xtn/capstone (now unavailable).

After a period of IPSuite being unmaintained, Andras Varga took over the development in July 2003. Through a series of snapshot releases in 2003-2004, modules got completely reorganized, documented, and many of them rewritten from scratch. The MPLS models (including RSVP-TE, LDP, etc) also got refactored and merged into the codebase.

During 2004, Andras added a new, modular and extensible TCP implementation, application models, Ethernet implementation and an all-in-one IP model to replace the earlier, modularized one.

The package was renamed INET Framework in October 2004.

Support for wireless and mobile networks got added during summer 2005 by using code from the Mobility Framework.

The MPLS models (including LDP and RSVP-TE) got revised and mostly rewritten from scratch by Vojta Janota in the first half of 2005 for his diploma thesis. After further refinements by Vojta, the new code got merged into the INET CVS in fall 2005, and got eventually released in the March 2006 INET snapshot.

The OSPFv2 model was created by Andras Babos during 2004 for his diploma thesis which was submitted early 2005. This work was sponsored by Andras Varga, using revenues from commercial OMNEST licenses. After several refinements and fixes, the code got merged into the INET Framework in 2005, and became part of the March 2006 INET snapshot.

The Quagga routing daemon was ported into the INET Framework also by Vojta Janota. This work was also sponsored by Andras Varga. During fall 2005 and the months after, ripd and ospfd were ported, and the methodology of porting was refined. Further Quagga daemons still remain to be ported.

Based on experience from the IPv6Suite (from Ahmet Sekercioglu's group at CTIE, Monash University, Melbourne) and IPv6SuiteWithINET (Andras's effort to refactor IPv6Suite and merge it with INET early 2005), Wei Yang Ng (Monash Uni) implemented a new IPv6 model from scratch for the INET Framework in 2005 for his diploma thesis, under guidance from Andras who was visiting Monash between February and June 2005. This IPv6 model got first included in the July 2005 INET snapshot, and gradually refined afterwards.

The SCTP implementation was contributed by Michael Tuexen, Irene Ruengeler and Thomas Dreibholz

Support for Sam Jensen's Network Simulation Cradle, which makes real-world TCP stacks available in simulations was added by Zoltan Bojthe in 2010.

TCP SACK and New Reno implementation was contributed by Thomas Reschka.

Several other people have contributed to the INET Framework by providing feedback, reporting bugs, suggesting features and contributing patches; I'd like to acknowledge their help here as well.