Castalia

A simulator for Wireless Sensor Networks
and Body Area Networks

Version 3.3

User's Manual

Athanassios Boulis
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NICTA

Contents

1 Introduction

Castalia is a simulator for Wireless Sensor Networks (WSN), Body Area Networks (BAN) and generally networks of low-power embedded devices. It is based on the OMNeT++ platform and can be used by researchers and developers who want to test their distributed algorithms and/or protocols in realistic wireless channel and radio models, with a realistic node behaviour especially relating to access of the radio. Castalia can also be used to evaluate different platform characteristics for specific applications, since it is highly parametric, and can simulate a wide range of platforms. The main features of Castalia are:

- Advanced **channel model** based on empirically measured data.
    - Model defines a map of path loss, not simply connections between nodes
    - Complex model for temporal variation of path loss
    - Fully supports mobility of the nodes
    - Interference is handled as received signal strength, not as separate feature
- Advanced **radio model** based on real radios for low-power communication.
    - Probability of reception based on SINR, packet size, modulation type. PSK FSK supported, custom modulation allowed by defining SNR-BER curve.
    - Multiple TX power levels with individual node variations allowed
    - States with different power consumption and delays switching between them
    - Realistic modelling of RSSI and carrier sensing
- Extended **sensing** modelling provisions
    - Highly flexible physical process model.
    - Sensing device noise, bias, and power consumption.
- Node **clock drift**
- MAC and routing protocols available.
- Designed for **adaptation** and **expansion**.

Concerning the last bullet, Castalia was designed right from the beginning so that the users can easily implement/import their algorithms and protocols into Castalia while making use of the features the simulator is providing. Proper modularization and a configurable, automated build procedure help towards this end. The modularity, reliability, and speed of Castalia is partly enabled by OMNeT++, an excellent framework to build event-driven simulators [OMNeT++ link].

What Castalia is not: Castalia is not sensor-platform specific. Castalia is meant to provide a generic reliable and realistic framework for the first order validation of an algorithm before moving to implementation on a specific sensor platform. Castalia is not useful if one would like to test code compiled for a specific sensor node platform. For such usage there are other simulators/emulators available (e.g., Avrora).

1.1 Why yet another simulator?

There is a variety of simulators that WSN researchers are using to cover their needs. Simulators that emulate a common processor found in sensor nodes (to test actual binary code written for certain platforms), simulators written in C++ or Matlab to test some first order property of an algorithm, or simulators used in traditional data networks modified in some way to serve the WSN community. So why try to build a new one?

It all started from our own needs in a WSN project. We wanted to test some communication patterns in simulation before moving in real systems. In order to do so we wanted accurate enough radio/channel models so that the simulation results would become meaningful and guide us in our search. We knew of the work by Zuniga et al. [1] that explained empirically measured data from WSN platforms (more specifically packet reception rate as a function of distance) by combining known wireless channel and radio models. We found that all the available WSN simulators were falling short of the current state of the art modelling done in sensor networks. Especially in communication where the impact to the result can be significant [5], models remain simplistic or unsuitable for short range low power communications despite the existence of proper models developed the last couple of years. This was the major reason we decided to build our own simulator. We used OMNeT++ as the base to build a reliable and fast event-driven simulator. Using OMNeT++ meant that we could just focus on the models and overall design and not on the event-driven simulation engine. Shortly after, we have decided to "up the ante", capture realistic node behaviour beyond the channel and build an open expandable and reliable simulator that has a chance of becoming a de facto standard for certain WSN simulation needs. More specifically, the need for early stage, platform-independent, algorithm/protocol validation. Since its initial inception and creation, Castalia has moved to new territories: BAN is another exciting area where realistic and reliable network-level simulators are needed. NICTA had a large scale project in BAN, that influenced Castalia's evolution. With our expertise in physical layer design, measurements and modeling, we had set out to make Castalia the most realistic BAN network simulator, by modelling the temporal variations and average path losses based on real on-body measurements.

2 Overview

Castalia is using OMNeT++ as its base so it is suggested that you have a fair understanding of the basic concepts of OMNeT although this is not required, especially if you want to use Castalia in a basic way (i.e., without building your own protocols/applications)

OMNeT's basic concepts are modules and messages. A simple module is the basic unit of execution. It accepts messages from other modules or itself, and according to the message, it executes a piece of code. The code can keep state that is altered when messages are received and can send (or schedule) new messages. There are also composite modules. A composite module is just a construction of simple and/or other composite modules.

2.1 Structure

Castalia's basic module structure is shown in the diagram below.

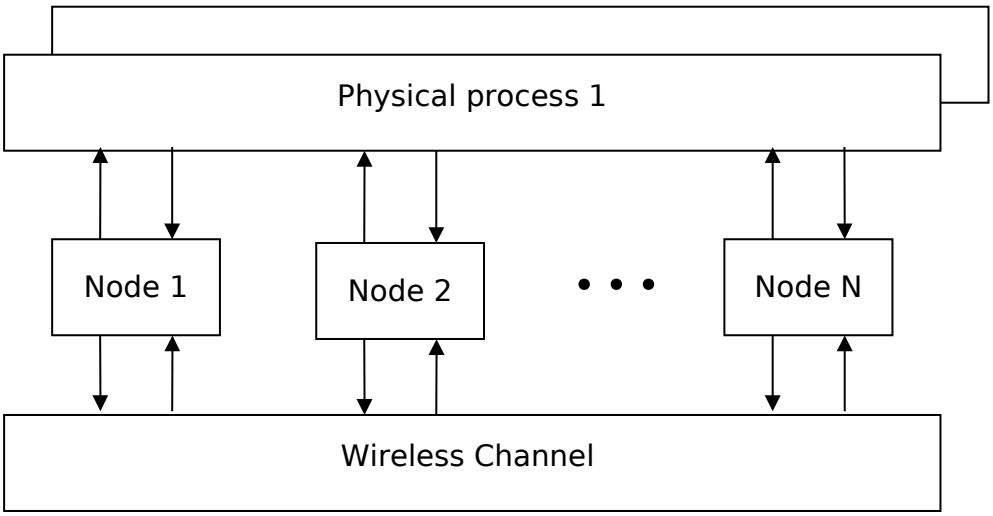

Figure 1: The modules and their connections in Castalia

Notice that the nodes do not connect to each other directly but through the wireless channel module(s). The arrows signify message passing from one module to another. When a node has a packet to send this goes to the wireless channel which then decides which nodes should receive the packet. The nodes are also linked through the physical processes that they monitor. For every physical process there is one module which holds the "truth" on the quantity the physical process is representing. The nodes sample the physical process in space and time (by sending a message to the corresponding module) to get their sensor readings.

There can be multiple physical processes, representing the multiple sensing devices (multiple sensing modalities) that a node has.

The node module is a composite one. Figure 2 shows the internal structure of the node composite module. The solid arrows signify message passing and the dashed arrows signify simple function calling. For instance, most of the modules call a function of the resource manager to signal that energy has been consumed. The Application module is the one that the user will most commonly change, usually by creating a new module to implement a. new algorithm. The communications MAC and Routing modules, as well as the Mobility Manager module, are also good candidates for change by the user, again usually by creating a new module to implement a new protocol or mobility pattern. Castalia offers support for building your own protocols, or applications by defining appropriate abstract classes (more on this topic in Chapter 5). All existing modules are highly tuneable by many parameters.

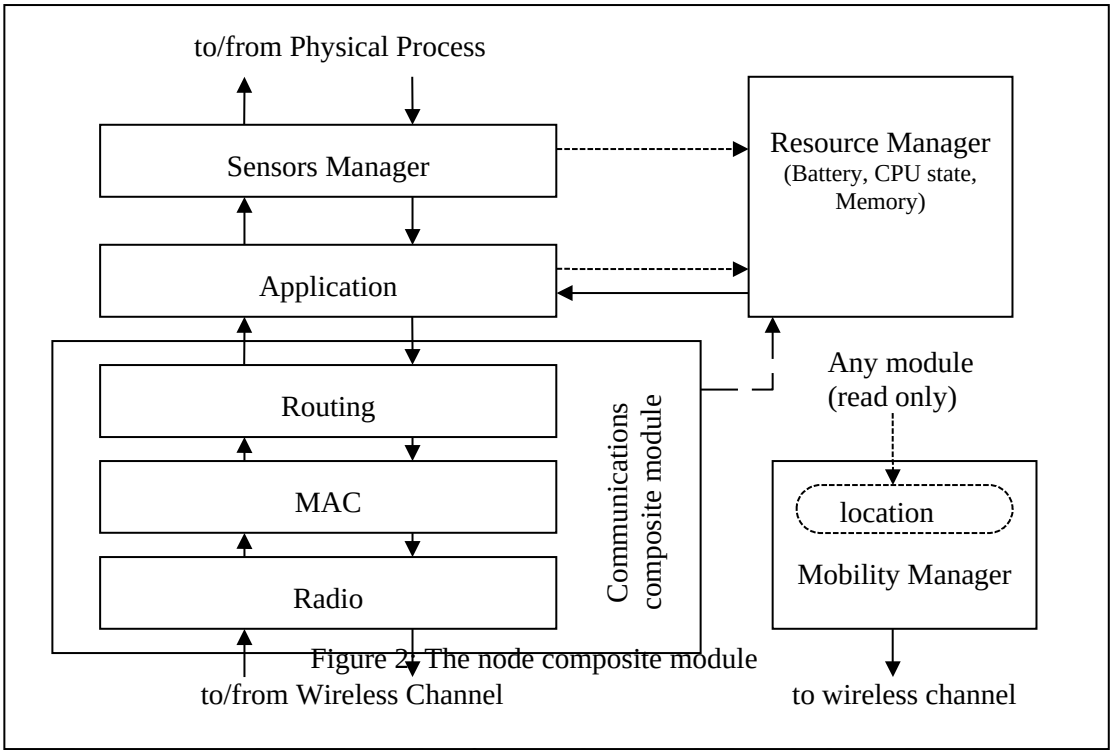

Figure 2: The node composite module

This structure depicted in the figures above and described in this chapter is implemented in Castalia with the use of the OMNeT++ NED language. With this language we can easily define modules, i.e., define a module name, module parameters, and module interface (gates in and gates out) and possible submodule structure (if this is a composite module). Files with the suffix "`.ned`" contain NED language code. The Castalia structure is also reflected in the hierarchy of directories in the source code. Every module corresponds to a directory which always contains a `.ned` file that defines the module. If the module is

composite then there are subdirectories to define the submodules. If it is a simple module then there is C++ code (.cc, .h files) to define its behaviour. This complete hierarchy of .ned files defines the overall structure of the Castalia simulator. Normally the user will not alter these files. Nevertheless, these files are dynamically loaded and processed (using a feature of OMNeT) so that any change does not require the recompilation of Castalia (unless of course new simple modules with new functionality appear).

In the rest of this document we will use these formatting conventions:

Commands given at the shell and output produced by them:

```
current_path$ commandline
Outputlines
Outputlines
```

Portions of configuration files (usually named omnetpp.ini):

```
Parameter1 = 1
Parameter2 = 2
```

C++ code or NED scripting code:

```
Code
```

Paths, file names, and parameter names will be written in `Courier` fonts. `Castalia/` is assumed to be the top-most level directory where all the Castalia files are installed.

3 Using Castalia

We assume here that you successfully installed both OMNeT and Castalia. Refer to the Installation Guide for details and troubleshooting. Since the release of Castalia 3.0, handling of input and output has changed considerably. We advise you to read this section even if you had previous experiences with Castalia 2.3b or earlier releases. Since Castalia 3.0, we have two scripts to help with running simulations and interpreting the results. They are called `Castalia` and `CastaliaResults` respectively. Since release 3.1 we also have `CastaliaPlot` to help you create graphs. They all reside in `Castalia/bin/`[1]. The executable of the simulator is called `CastaliaBin` resides in `Castalia/` but you will not need to invoke it directly.

3.1 Running the first simulation

It's time to dive in and run our first simulation. Go to the directory `Castalia/Simulations/radioTest`. It should include one file: `omnetpp.ini`. This is a configuration file that defines our simulation scenario(s). Let us run the input script with no arguments and see what we get:

```
~/Castalia/Simulations/radioTest$ ../../bin/Castalia
List of available input files and configurations:
* omnetpp.ini
        General
        InterferenceTest1
        InterferenceTest2
        CSinterruptTest
        varyInterferenceModel
```

Executed with no arguments, the script searches the current directory for valid configuration files. If it finds a file, it then parses it and prints the name of the configurations contained in it (more about configurations shortly). In our case it found just one file with five configurations.

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1 It is suggested that you add Castalia/bin/ in your PATH env variable. In the command line examples we give in this manual, we assume that Castalia/bin is in the path. If you are using bash you simply do

`$ export PATH=$PATH:~/Castalia/bin`

(assuming Castalia's dir is named "Castalia" and it is installed under your home dir)

Also do not forget to add this export statement in your `.bash_profile` file

To see how we can use the `Castalia` input script to do something more exciting, ask for help. Run it with `-h` as argument.

```
~/Castalia/Simulations/radioTest$ ../../bin/Castalia -h
Usage: Castalia [options]

Options:
  -h, --help            show this help message and exit
  -c CONFIG, --config=CONFIG
                        A list of configuration names to use, comma
                        separated configurations will be joined
                        together, configurations listed in brackets
                        will be interleaved
  -i FILE, --input=FILE
                        Select input configuration file, default is
                        omnetpp.ini
  -d, --debug           Debug mode, will display results from each
                        CastaliaBin execution
  -o FILE, --output=FILE
                        Select output file for writing results,
                        generated from current date by default
  -r N, --repeat=N      Number of repetitions for each unique
                        scenario
```

We see that we can instruct the `Castalia` script to use a specific file with the `-i` switch (although we do not need to in our case, omnettpp.ini is the default) and use the `-c` switch to choose a configuration within this file. For the moment do not mind the help-text mentioning that a list of configuration can be given, and just run it with one configuration. Let's use `General`, which is always present in an omnetpp.ini file and is considered the default configuration.

```
~/Castalia/Simulations/radioTest$ ../../bin/Castalia -c General
Running Castalia: Configuration 1/1       Run 1/1     Complete 100%
      Time taken 0:00:00.101000
```

You've just run your first simulation! Let's see what's new in our directory.

```
~/Castalia/Simulations/radioTest$ ls
100806-222319.txt  Castalia-Trace.txt  omnetpp.ini
```

There are 2 new files created: `100806-222319.txt` is Castalia's standard output file and its name is in the form `YYMMDD-HHMMSS.txt`. You can freely rename this file if you wish. You can also open it to read it (it is human readable) but it is not supposed to be viewed this way. Normally you will process this file with `CastaliaResults`. We will see how to do this in section 3.3. The other file produced is a trace file named `Castalia-Trace.txt`. It contains a trace of all events that you requested to be recorded by "turning on" some parameters in the omnetpp.ini file. By default all tracing is turned off, but for this simulation example we wanted to activate just the tracing from the application module of node 0. Open the file and have a look.

```
~/Castalia/Simulations/radioTest$ less Castalia-Trace.txt

0.027540267327  SN.node[0].Application       Not sending packets
3.868527053713  SN.node[0].Application       Received packet #18 from node 1
4.068529304763  SN.node[0].Application       Received packet #19 from node 1
4.268531555813  SN.node[0].Application       Received packet #20 from node 1
4.468533806863  SN.node[0].Application       Received packet #21 from node 1
4.668536057913  SN.node[0].Application       Received packet #22 from node 1
…
```

Each line is a trace event. The first item in the line is the simulation time that the event happened. Second item is the full name of the module that produced this trace line. In the example above all lines are produced by the Application module of node 0. Finally, the last item is the trace message itself. In the example above most messages notify us of packet received by node 1, also printing the packet's serial number.

But what is this simulation supposed to do?

We created the radioTest simulation scenarios so users can see the results of realistic modeling and also see some of Castalia's features in action. The first scenario (the General configuration we just run) tests reception, as a receiver (node 0) moves through the area of two transmitters (nodes 1 and 2). The transmitters are placed far enough so there is no interference between them. The receiver moves in a straight line back and forth and when it is close to each of the two transmitters it should receive their packets. For this simulation we have turned off shadowing effects so that the successful-reception-distance is identical for the two transmitters (still there are random effects in the radio reception, so the numbers of received packets by the two transmitters are not identical). The InterferenceTest1 and InterferenceTest2 scenarios have the receiver static and one of the transmitters moving. The

idea there is to show the effect of interference with the use of mobility. In InterferenceTest1 the interfering node passes through the middle of the distance between node 1 and 0, and thus just causes collisions. In InterferenceTest2 though it passes very close to the receiver (compared to the other transmitter) and thus even though initially it creates collisions, when sufficiently close, its SINR is high enough for its packets to be received (despite interference from the transmissions of static node 1). Figure 3 illustrates these interactions. From left to right the 3 boxes depict: General, InterferenceTest1, InterferenceTest2

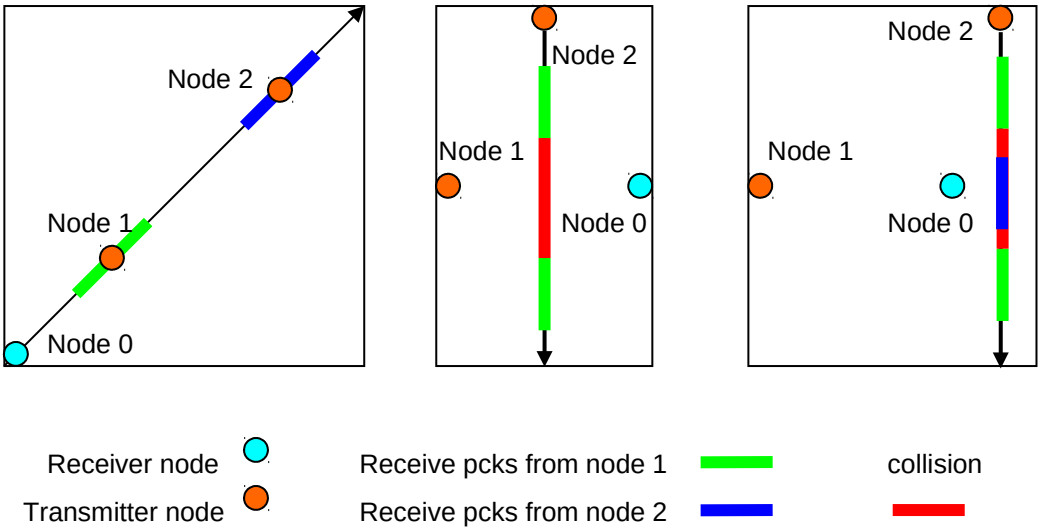


Figure 3: The General, InterferenceTest1, and InterferenceTest2 configurations

Run the other two simulation scenarios and look at the resulting Castalia-Trace.txt files (delete the old trace files if you do not want the new traces appended in the old file).

```
~/Castalia/Simulations/radioTest$ rm Castalia-Trace.txt
~/Castalia/Simulations/radioTest$ Castalia -c InterferenceTest1
Running configuration 1/1
```

Are the traces as expected? You should be able to see the patterns of reception and breaking of reception as depicted in figure 3.

Let’s us look more deeply into the omnetpp.ini file.

3.2 Understanding the configuration file

As described in Chapter 2, Castalia has a modular structure with many interconnecting modules. Each one of the modules has one or more *parameters* that affect its behavior. An NED file (file with extension .ned in the Castalia source code) defines the basic structure of a module by defining its input/output gates and its parameters. In the NED file we can also define *default values* for the parameters. A configuration file (usually named omnetpp.ini and residing in the Simulations dir tree) assigns values to parameters, or just reassigns them to a different value from their default one. This way we can build a great variety of simulation scenarios. Open the file `Simulations/radioTest/omnetpp.ini`

Note that any string after a # character is a comment. The configuration file starts with the General section. Every OMNeT configuration file has a General section. There you define the basic scenario that this file describes. Parameters such as the simulation time and number of nodes do not have any default values and must be defined in this section. Below are the first few lines from the `radioTest/omnetpp.ini` file (comments removed)

```
[General]
include ../Parameters/Castalia.ini

sim-time-limit = 100s

SN.field_x = 200        # meters
SN.field_y = 200        # meters

SN.numNodes = 3
```

The first line in the General section is an include command. As the name suggests, the command includes the contents of the file it gets as an argument. In the particular example we include a file we named Castalia.ini and it contains some basic parameter assignments[2] that every Castalia simulation needs. So when you create a Castalia configuration file, always include Castalia.ini in it.

Then we define the simulation time (here assigned to 100 secs). This is the only generic OMNeT parameter we assign in a Castalia configuration file. We can see that all other parameter start their name with `SN`. SN is the topmost composite module (or “network” as OMNeT calls it). The name SN stands for Sensor Network. There are a few parameters that the network takes such as the field size, the number of nodes, and the deployment type. The

2 Castalia.ini assigns some parameters affecting general OMNeT execution, as well as parameters that map the different Random Number Generators (RNGs) to modules.

field size is given by 3 real numbers, each for axes x,y,z. One can define only 2 of the axes if desired (the third one will take the value 0 by default). Number of nodes is given by an integer. The parameter `SN.deployment` is a string that describes where the nodes are placed on the field. If left undefined (as in our example above) then the location of the nodes is determined by the xCoor, yCoor, zCoor parameters of each node. These are usually manually assigned in the omnetpp.ini file. When defined, `SN.deployment` can be one of the following types:

"uniform" → nodes are placed in the field using a random uniform distribution

"NxM"→ N and M are integer numbers. Nodes placed in a grid of N nodes by M nodes

"NxMxK" → same as above but for 3 dimensions

"randomized_NxM" → a grid deployment with randomness in the position of the nodes. If Gx and Gy is the grid spacing in axes x and y, and (Xi, Yi) are the grid position of node i then the randomized grid position is (Xi+Rx, Yi+Ry) where Rx and Ry are numbers uniformly drawn from [(-1/3)Gx…(1/3)Gx] and [(-1/3)Gy…(1/3)Gy]

"randomized_NxMxK" → same as above but for 3 dimensions

"center" → node put in the centre of the field

We can even define **mixed** deployments by using this string format:
[N1..N2]->type;[N2..N3]->type;… where Nx are node IDs, and types is one of the options given above

After we set these top level parameters, we go into setting module parameters. When setting a module parameter, the full name of the module is given revealing the module hierarchy structure. Here is an example from our configuration file, setting some parameters of the wireless channel.

```
# important wireless channel switch to allow mobility
SN.wirelessChannel.onlyStaticNodes = false
SN.wirelessChannel.sigma = 0
SN.wirelessChannel.bidirectionalSigma = 0
```

We will explain the meaning and use of all parameters in Chapter 4 (Modeling in Castalia). In this section we present some basic concepts and syntax rules of Castalia configuration files.

For instance, how do we set radio parameters? Remember that the radio is part of the Communication composite module of *every* node. So there are as many Radio modules as there are nodes. How do we set all of them easily? Here's how:

```
SN.node[*].Communication.Radio.RadioParametersFile =
                                    "../Parameters/Radio/CC2420.txt"
SN.node[*].Communication.Radio.TxOutputPower = "-5dBm"
```

These two lines set 2 parameters of the Radio module. The RadioParametersFile is a specially formatted file defining the basic operational properties of a radio (more on Chapter 4). The second parameter, TxOutputPower sets the power that the radio transmits its packets. Notice how we access all the radio modules in all the nodes with the use of [*].

The sensor network compound module (SN) contains many Node sub-modules. These are addressed in the form of an array. For instance, here's how to set the parameter `xCoor` (the x coordinate of the location of a node) of the node with ID=9:

```
SN.node[9].xCoor = 10.5
```

However, most of the time we need to massively assign values for all the nodes of the sensor network. This is possible by using wildcards like:

`[*]` → all indexes

`[3..5]` → indexes 3,4,5

`[..4]` → indexes 0, 1, 2, 3, 4

`[5..]` → indexes 5 till the last one

Reading on in our example omnetpp.ini file we see that parameters relating to the maximum allowed packet size are set in all communication layers:

```
SN.node[*].Communication.Routing.maxNetFrameSize = 2500
SN.node[*].Communication.MAC.maxMACFrameSize = 2500
SN.node[*].Communication.Radio.maxPhyFrameSize = 2500
```

We have already set the kind of radio we want to use, by setting RadioParametersFile. How do we instruct Castalia which MAC protocol and which Routing protocol to use? This is achieved by two Communication module parameters

```
SN.node[*].Communication.MACProtocolName
SN.node[*].Communication.RoutingProtocolName
```

These are set by default to "`BypassMAC`" and "`BypassRouting`". These are module names that in essence implement no MAC functionality and no Routing functionality. For the radioTest simulation we did not need any MAC or Routing so we left these parameters

assigned to their default value (i.e., they are not mentioned in the omnetpp.ini file). If you want to see the default values for any parameter just go to the .ned file that describes that module. For the parameters mentioned above you can look in:

`src/node/communication/CommunicationModule.ned`

If you look at the BANtest/omnetpp.ini you will see MACProtocolName being assigned

```
SN.node[*].Communication.MACProtocolName = "BaselineBANMac"
```

The important thing to note here is that by assigning a name to this parameter we are also choosing a specific module for our MAC. So by altering these parameters we can dynamically control the composition of modules in our simulation[3]. The consequence of this feature is that depending on the module you choose, the parameters available to you are also changing since different MAC modules support different parameters. There are four kinds of modules that are dynamically selected in a Castalia configuration file. We have already seen the 2 kinds: MAC and Routing modules. The other 2 are Application modules and MobilityManager modules.

Here is how we set our radioTest simulation to use the Application module we want:

```
SN.node[*].ApplicationName = "ThroughputTest"
SN.node[*].Application.packet_rate = 5
SN.node[*].Application.constantDataPayload = 2000
# application's trace info for node 0 (receiving node)
# is turned on, to show some interesting patterns
SN.node[0].Application.collectTraceInfo = true
```

By setting the `ApplicationName` we also choose the application module. `ThroughputTest` application has all nodes sending traffic to a sink node. We can easily modify the packet rate and the packet size as you can notice. The sink node is by default node 0 and we have not changed this here. Also notice how the last line shown above, activates the collecting of traces for the Application module of node 0. This is why the `Castalia-Trace.txt` files we examined in section 3.1 were created and this is why they only contained events from the application module of node 0. *All Castalia modules* have a `collectTraceInfo` parameter. By default, collection of traces is deactivated (parameter set to false).

Then follows a section where we set the starting locations for our 3 nodes manually (remember that we left `SN.deployment` to its default value: “custom”). We write “starting

3 This is achieved thanks to OMNeT’s dynamic module loading capability and also its ability to define parametric module names in .ned files.

locations” because the nodes can be mobile. Indeed, we see that node 0 is using `LineMobilityManager` as the mobility manager module. The other two nodes have the default mobility manager: `NoMobilityManager`, which is used to describe static nodes.

```
SN.node[0].xCoor = 0
SN.node[0].yCoor = 0
SN.node[1].xCoor = 50
SN.node[1].yCoor = 50
SN.node[2].xCoor = 150
SN.node[2].yCoor = 150

SN.node[0].MobilityManagerName = "LineMobilityManager"

SN.node[0].MobilityManager.updateInterval = 100
SN.node[0].MobilityManager.xCoorDestination = 200
SN.node[0].MobilityManager.yCoorDestination = 200
SN.node[0].MobilityManager.speed = 15
```

The `LineMobilityManager` module moves the node in a straight line segment (back and forth). The straight line segment is defined by the starting location of a node and the destination location given by the xCoorDestination, yCoorDestination parameters of the mobility module. We also define the speed and the update interval that the wireless channel module will be updated of the node’s current position.

After these lines we see a new section: a new *configuration*.

```
[Config InterferenceTest1]
SN.node[0].MobilityManagerName = "NoMobilityManager"
SN.node[1].MobilityManagerName = "NoMobilityManager"
SN.node[2].MobilityManagerName = "LineMobilityManager"

SN.node[0].xCoor = 10
SN.node[0].yCoor = 50

SN.node[1].xCoor = 0
SN.node[1].yCoor = 50

SN.node[2].xCoor = 5
SN.node[2].yCoor = 0

SN.node[2].MobilityManager.updateInterval = 100
```

```
SN.node[2].MobilityManager.xCoorDestination = 5
SN.node[2].MobilityManager.yCoorDestination = 100
SN.node[2].MobilityManager.speed = 5
```

In this configuration, node 2 is the mobile one, instead of node 0, and nodes are much closer to each other (so that we can simulate interesting interference behaviour).

Yet another configuration section follows with slightly different node locations, which we do not show here. Instead we draw your attention at the end of the file, where a very short configuration section resides. Here it is:

```
[Config varyInterferenceModel]
SN.node[*].Communication.Radio.collisionModel = ${InterfModel=0,1,2}
```

Notice how we do not assign just one value to the parameter but a series of values. This is a feature of OMNeT 4.0 and later versions. You can look at the OMNeT manual for a complete list of the ways you can assign parameters, but the essence of this multiple-value assignment is that simulation will run many times, each time assigning one of the values. So given the example above we will run the simulation 3 times. The name “InterfModel” in the curly braces will just be used as a label in the output produced and helps us parse the output more easily.

If you have more than one parameter that takes multiple values, then all combinations will be run. In the example below we have 2 parameters taking 3 values each, which means 9 possible parameter combinations, thus 9 simulation runs.

```
SN.node[1].Communication.Radio.TxOutputPower = ${TxPower="-5dBm", "-10dBm", "-15dBm"}
SN.node[0].Communication.Radio.CCAthreshold = ${CCAthreshold=-95, -90, -85}
```

You can even do more complicated things such as putting constraints, so that not all possible combinations are executed. Here’s an example from `BANtest/omnetpp.ini`:

```
SN.node[*].Communication.MAC.scheduledAccessLength = ${schedSlots=6,5,4,3}
SN.node[*].Communication.MAC.RAP1Length = ${RAPslots=2,7,12,17}
constraint = $schedSlots * 5 + $RAPslots == 32
```

The example above will only execute 4 combinations: (6,2), (5,7), (4,12), (3,17).

3.3 Using the Castalia and CastaliaResults scripts

OMNeT allows you to choose just one of the configurations defined in a configuration file. That is, if you use the simulator binary directly (i.e. `CastaliaBin`) you can choose an input configuration file and one configuration. When choosing a configuration the parameters from the General section are used and set, and if the configuration redefines them, then their value is overwritten. Although this feature is an improvement over older versions, its usefulness is limited. Notice for example, the configuration on varying the collision model we examined earlier. If we choose it using OMNeT's standard feature it will only be applied in the General section scenario. If we would like the same effect in the Interference scenarios then we would have to explicitly include that line in each configuration. If we also wanted to vary the Tx power but not vary the collision model, then we would have to explicitly write another set of configurations. The problem is that you cannot easily *combine* configurations. You have to explicitly write the combinations. Furthermore, you cannot easily execute more than one configuration at a time. We can overcome these restrictions by using the Castalia script.

With the Castalia script we can easily give a list of configurations to be combined.

For example, we can write "Castalia –c InterferenceTest1,varyInterferenceModel" or "Castalia –c InterferenceTest2,varyInterferenceModel" no need to create the combination explicitly in the omnetpp.ini file. Moreover we have the ability to define more than one configuration to be executed by listing different configurations in braces. Castalia –c [A,B] will execute the simulation with configuration A and then another simulation with configuration B.

Castalia –c [A,B]C,D[E,F] will execute 4 combined configurations:

A,C,D,E ← this is a combination (or concatenation) of the 4 simple configs listed

B,C,D,E

A,C,D,F

B,C,D,F

If you try to combine two or more configurations that have at least one overlapping parameter (i.e. same parameter is defined in two or more configurations) then you will get an error message from the script. For example if you tried:

```
radioTest$ Castalia -c InterferenceTest1,InterferenceTest2
ERROR: conflicting values for parameter 'SN.node[2].xCoor' in base
configurations: '5' and '22'
```

Let us use the power of the `Castalia` script to run a useful simulation:

```
$ Castalia -c [InterferenceTest1,InterferenceTest2]varyInterferenceModel
Running configuration 1/2
Running configuration 2/2
```

A new output file was created (in our system 100809-004640.txt) and `Castalia-Trace.txt` got appended with new traces. How would you check the results? You could open the output file or the trace, but there is a lot of text to parse and understand. Remember that for each of the configurations we have 3 collision models tried, so in total we had 6 simulations run. We need a way to process and summarize the results. This is what the script CastaliaResults is for. Let's run it with no arguments to see what it gives us:

```
~/Castalia/Simulations/radioTest$ CastaliaResults

Castalia output files in current directory:
+------------------+--------------------------------+------------------+
|                  | Configuration                  | Date             |
+------------------+--------------------------------+------------------+
| 100807-160236.txt | General (1)                   | 2010-08-07 16:02 |
| 100808-014651.txt | InterferenceTest1 (1)         | 2010-08-08 01:46 |
| 100809-004640.txt | [InterferenceTest1,Interference | 2010-08-09 00:46 |
|                  |  Test2]varyInterferenceModel (1)|                  |
+------------------+--------------------------------+------------------+
```

It gives us a list of valid Castalia output files (also called result files) with information about the configuration that created them and the date they were created. The number in the parentheses (1) denotes the repetitions (with different seeds) each configuration was executed. You can use the –h option to get help on the arguments the script can take. Let's run the script giving it one of the results file as input (use the –i switch)

```
radioTest$ CastaliaResults -i 100809-004640.txt

+--------------------+--------------------------------+------------+
|             Module |                         Output | Dimensions |
+--------------------+--------------------------------+------------+
|        Application | Application level latency, in ms | 1x2(11)    |
|                    |       Packets received per node | 1x2        |
| Communication.Radio |                RX pkt breakdown | 3x1(6)     |
|                    |                       TXed pkts | 2x1        |
|    ResourceManager |                 Consumed Energy | 3x1        |
+--------------------+--------------------------------+------------+
NOTE: select from the available outputs using the -s option
```

`CastaliaResults` parses the file and finds out what output is recorded by the different modules. Application for example produces two kinds of output relating to packet latency and packets received. Each output has its dimensions NxM.

N is the number of modules that produced this output. Modules that are instantiated only once (e.g., the wirelessChannel) will always have N=1. Modules that are instantiated n times (e.g., the node and all of its submodules) can have N equal up to n. In the example above, even though there are 3 Application modules (recall that radioTest simulations instantiate 3 nodes), only one of them is producing output. This is the Application module of node 0, since this is the only one receiving packets.

M, is the number of different indices, an output from a *single* module has. When defining an output, it is possible to give it an index parameter. Usually this is used to differentiate output relating to different nodes. For example the "Packets received per node" output has an index specifying the sender of the packet. This way we can keep track of how many packets did a node receive from the different senders. If an output does not have an index (e.g., the consumed energy output of a node) then M=1.

Finally, if an output from a single module and for a single index is not scalar, then we write its multiplicity in parentheses. For example, the latency output is a histogram with 11 time buckets. As another example, the Radio received packet breakdown has 6 different types of packets. The types are naming the different conditions the packets failed or succeeded.

The note at the end of the output above urges us to use the `-s` switch ('s' standing for 'show') to select among the possible outputs. You just give it a regular expression and it will present the results from the output names that match the regular expression. Let's say we want to see what the application received packets results are:

```
radioTest$ CastaliaResults -i 100809-004640.txt -s received
Application:Packets received per node
+------------------+--------------+--------------+---------------+
|                  | InterfModel=0 | InterfModel=1 | InterfModel=2 |
+------------------+--------------+--------------+---------------+
| InterferenceTest1 | 335.5         | 24            | 199           |
| InterferenceTest2 | 332.5         | 13            | 24.5          |
+------------------+--------------+--------------+---------------+
```

We see the results for both interference tests for all 3 collision modes in a nice 2×3 matrix. The results in each cell are averages for all modules that produced this output and all indices of the output. In our case it is the average received packets per node at node 0 (since the app of node 0 is the only module that produces this output as we mentioned). The average

is calculated over 2 indices (sender node 1 and 2), but if one result is zero then it do not count in the average. Instead of the average we can see the sum by using the switch `--sum`.

```
radioTest$ CastaliaResults -i 100809-004640.txt -s received --sum
Application:Packets received per node
+------------------+--------------+--------------+--------------+
|                  | InterfModel=0 | InterfModel=1 | InterfModel=2 |
+------------------+--------------+--------------+--------------+
| InterferenceTest1 | 671          | 24           | 199          |
| InterferenceTest2 | 665          | 23           | 49           |
+------------------+--------------+--------------+--------------+
```

This sum info is trivial in our case, since we know that we always have 2 indices so we can just multiply the average results by 2, but in some cases the `--sum` switch can be very useful. For example, when we do not know the number of elements that contribute to the average, or the number is changing for different cells of the output table. Returning to our specific example, the average (or sum) table gives us an understanding of the situation but it would be more informative if we could see the results for the individual sender. We can do this by using the `-n` switch ('n' standing for 'node'). Let's try it:

```
radioTest$ CastaliaResults -i 100809-004640.txt -s received -n
Application:Packets received per node
+---------------------------------+---------+---------+
|                                 | Index=1 | Index=2 |
+---------------------------------+---------+---------+
| InterferenceTest1,InterfModel=0 | 499     | 172     |
| InterferenceTest1,InterfModel=1 | 24      | 0       |
| InterferenceTest1,InterfModel=2 | 199     | 0       |
| InterferenceTest2,InterfModel=0 | 494     | 171     |
| InterferenceTest2,InterfModel=1 | 23      | 0       |
| InterferenceTest2,InterfModel=2 | 25      | 24      |
+---------------------------------+---------+---------+
```

A new dimension called "index" was added to the results table. The table of results became 6×2 and now the columns are labeled with an index which is the ID of the sender node. Note that for a given row, the sum of the cells is equal to the contents of a cell from the previous table (the table we got with --sum). But now we can see how this sum breaks down. We see that when interference model = 0 is used (i.e., no collisions) then node 0 receives the most packets from both node 1 and 2. Node 2 moves, so it is often outside the range of node 0. That's why fewer packets are received from it. There is some randomness at the Radio module (packet reception probability is based on SNR) so the packets received from node 1

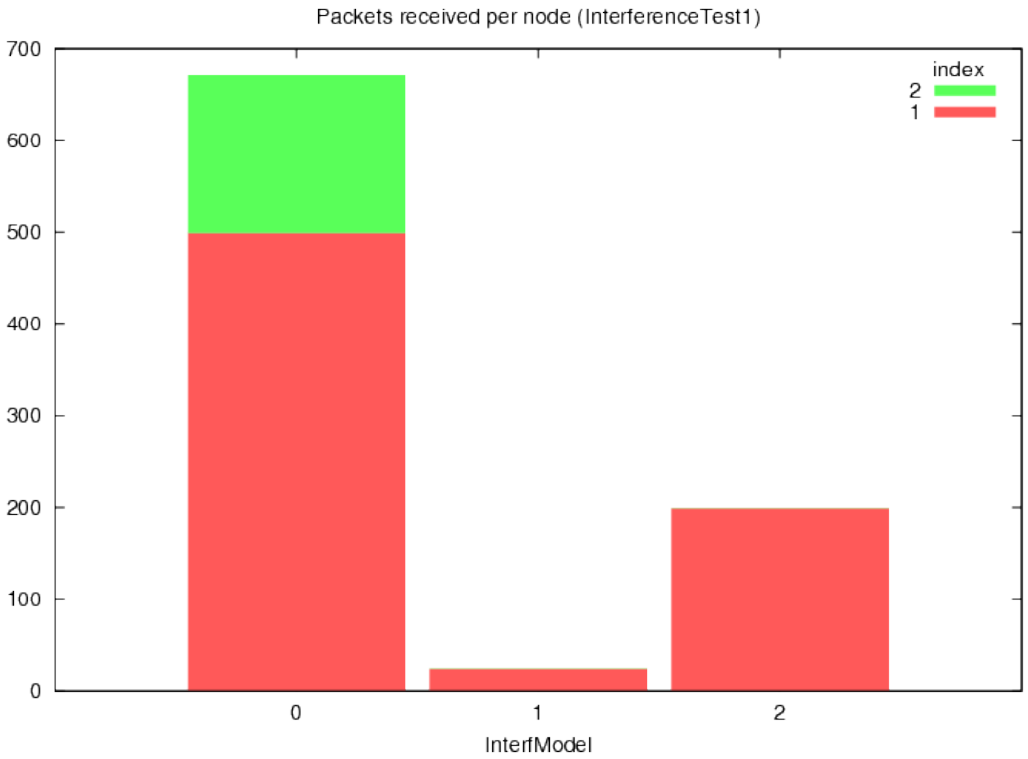
are not exactly equal in both Interference Tests. When collision model = 1 is used (i.e., simple model based on the notion of interference range) that creates more collisions than reality. We see that very few packets get through. Finally, when we use model=2 (i.e., additive interference model) then this takes into account the dynamic SINR of each packet. We see that node 2 actually manages to get some packets through as we described in Figure 3. For a detailed explanation of the different collision models refer to Chapter 4 (section 4.2.3).

Since Castalia 3.1 it is also easy to **automatically draw graphs** straight from the output of `CastaliaResults`, using the `CastaliaPlot` script. Here are a couple of examples (do not worry about the syntax of the command lines for now; we will see them in detail in the following sections):

Let us draw the packets received per node for Interference Test 1 while we vary the interference model

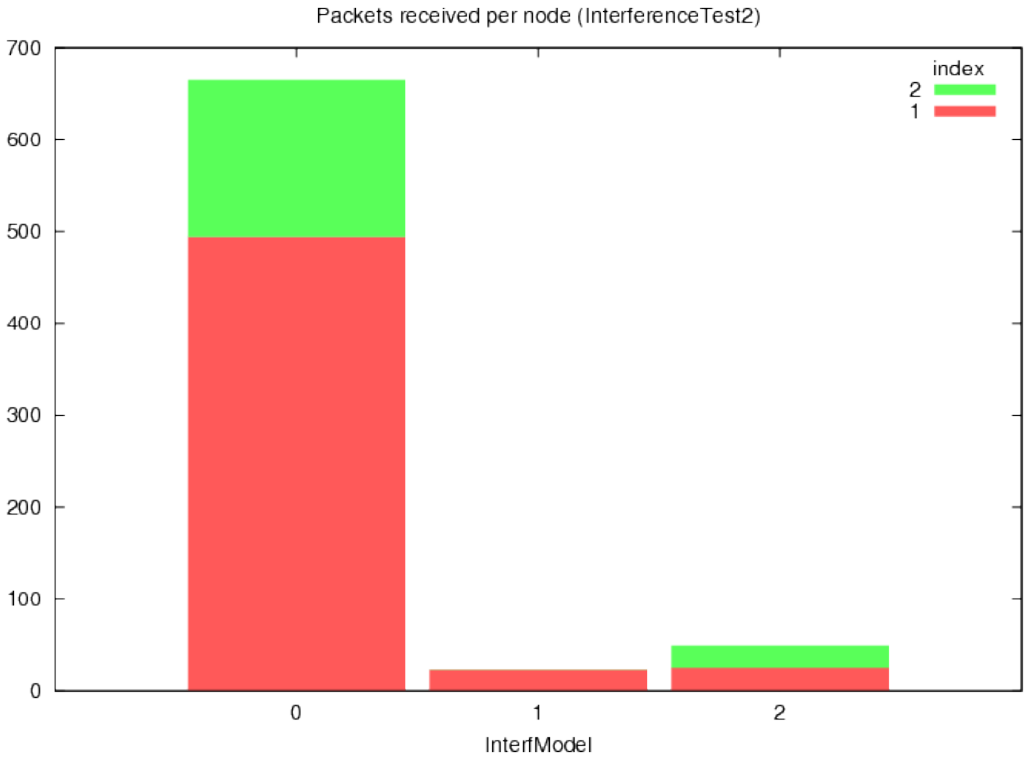
```
radioTest$ CastaliaResults -i 101209-235427.txt -s received -n -f Test1 |
CastaliaPlot -o interfTest1-app-varyModel.png -s stacked
```

This is the file interfTest1-app-varyModel.png produced:



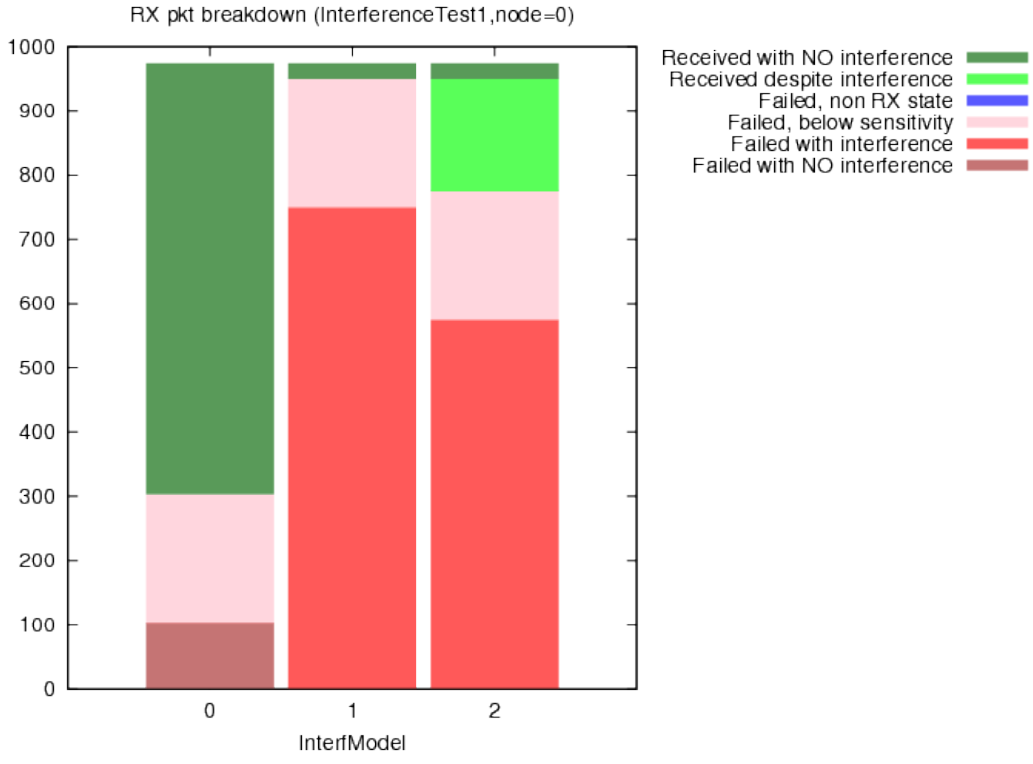
Or we can draw the same output for Interference Test 2 (we can draw them both in one graph if we like, but the x axis labels become too busy).

```
radioTest$ CastaliaResults -i 101209-235427.txt -s received -n -f Test2 |
CastaliaPlot -o interfTest2-app-varyModel.png -s stacked
```



Or we can look at the output of a different module than the application. For instance we can look at the breakdown of packets at the radio of node 0, for Interference Test 1 and for different interference models.

```
radioTest$ CastaliaResults -i 101209-235427.txt -s RX -n -f Test1.*node=0 |
CastaliaPlot -o interfTest1-RadioBrdown-varyModel.png -s stacked --
colors=radioBrdown -l "outside width -7"
```



Let us now move to a different simulation scenario and a different application altogether. The *connectivity map* application: This application is designed to produce a connectivity map of the network by finding out the link quality between nodes. Each node is programmed to transmit 100 packets at a unique timeslot, so that there are no collisions with other nodes. A node –when not transmitting– constantly listens for incoming packets, and when one is received, it increases the counter of the packets heard from the sender node. At the end of the simulation the counters are written as application output using the sender node as index. Go to `Simulations/connectivityMap/` and inspect the omnetpp.ini file

The configuration file describes a grid of 3nodes×3nodes (9 nodes in total). The General configuration has a wireless channel with no shadowing randomness and the radio is using a low Tx power. Let's run it and inspect the results.

```
connectivityMap$ Castalia -c General
Running configuration 1/1

connectivityMap$ ls
100809-145319.txt  omnetpp.ini

connectivityMap$ CastaliaResults -i 100809-145319.txt
+---------------------+------------------+------------+
|              Module |           Output | Dimensions |
+---------------------+------------------+------------+
|         Application | Packets received | 9x9        |
| Communication.Radio | RX pkt breakdown | 9x1(3)     |
|                     |        TXed pkts | 9x1        |
|     ResourceManager |  Consumed Energy | 9x1        |
+---------------------+------------------+------------+
NOTE: select from the available outputs using the -s option
```

We see that the Application module output "Packets received" is 9×9. This means that there are 9 modules reporting and for each module there are 9 indices (each corresponding to other nodes + the self node). Simply printing the result of that output will give us the average on these 9×9 (= 81) outputs. This will be the average link quality over all the links[4].

```
connectivityMap$ CastaliaResults -i 100809-145319.txt -s received
Application:Packets received
+--------+
|        |
```

4 It is the average of link quality for links that are not 0%, i.e. at least one packet was successfully received.

```
+--------+
| 88.225 |
+--------+
```

This in not such an interesting result, on its own. It would be much more interesting if we could see the quality of individual links. How many packets out of the 100 did each link (node A→ node B) was able to receive. We need to show individual outputs, not the average. We already mentioned that if we want to expand an output to its dimensions we use the –n switch. Let's try it.

```
connectivityMap$ CastaliaResults -i 100809-145319.txt -s packets -n

Application:Packets received
+--------+-------+-------+-------+-------+-------+-------+-------+-------+-------+
|        |Node=0 |Node=1 |Node=2 |Node=3 |Node=4 |Node=5 |Node=6 |Node=7 |Node=8 |
+--------+-------+-------+-------+-------+-------+-------+-------+-------+-------+
|index=0 | 0     | 100   | 0     | 99    | 73    | 0     | 0     | 0     | 0     |
|index=1 | 100   | 0     | 100   | 70    | 100   | 72    | 0     | 0     | 0     |
|index=2 | 0     | 100   | 0     | 0     | 73    | 100   | 0     | 0     | 0     |
|index=3 | 100   | 75    | 0     | 0     | 100   | 0     | 100   | 70    | 0     |
|index=4 | 78    | 100   | 72    | 100   | 0     | 100   | 66    | 100   | 64    |
|index=5 | 0     | 64    | 100   | 0     | 100   | 0     | 0     | 65    | 100   |
|index=6 | 0     | 0     | 0     | 100   | 72    | 0     | 0     | 100   | 0     |
|index=7 | 0     | 0     | 0     | 69    | 100   | 72    | 100   | 0     | 100   |
|index=8 | 0     | 0     | 0     | 0     | 75    | 100   | 0     | 100   | 0     |
+--------+-------+-------+-------+-------+-------+-------+-------+-------+-------+
```

Now we can see a map of connectivity! Each column is the results reported by a node. That is, each column i, is the link qualities of all incoming links to node i. Looking at the first column we can see that node 0 can hear nodes 1 and 3 perfectly and node 4 at 78%. This is expected as nodes 1 and 3 are the closest to node 0 (being immediately to the right and down of node 0) while node 4 is the next closest node (being on the right-down diagonal). Node 4 has the best connectivity (as expected) as it can listen to all 8 nodes around it.

What would happen if we varied the Tx Power? Or varied the sigma of the wireless channel (i.e. the randomness of the shadowing)? If you look into the omnetpp.ini file you will see that we have appropriate configurations for these questions. So we can run:

```
connectivityMap$ Castalia -c varyTxPower
Running configuration 1/1
connectivityMap$ Castalia -c varySigma
Running configuration 1/1
```

Using CastaliaResults, we can look into the application received packets produced by the first simulation.

```
connectivityMap$ CastaliaResults -i 100810-020129.txt -s packet
```

We can try to look at an expanded view using the `-n` switch. This will result in a long table since the 9×9 results showing the connectivity map will be multiplied 4 times (each time for a different TxOutputPower value) If we wish to limit the portion of the table shown, we can filter the rows with the `-f` switch. For instance, using `-f 5dBm` will print only rows that contain "5dBm" in their labels:

```
connectivityMap$ CastaliaResults -i 100810-020129.txt -s packet -n -f 5dBm
```

Or we can be even more specific and choose the rows that have "5dbm" and "=5" with any string in between (`-f` switch accepts Regular Expressions[5]) so it is easy to do:

```
$ CastaliaResults -i 100810-020129.txt -s packet -n -f 5dBm.*=5
```

3.4 Using CastaliaPlot to create graphs

We have already seen some examples of using `CastaliaPlot` in the previous section. In this section we explain the basics of the functionality this script offers. More advanced usage examples are given in subsequent sections as we use `CastaliaPlot` in conjunction with `CastaliaResults` to draw graphs of interest. `CastaliaPlot` is designed to take the output of `CastaliaResults` as input. You have probably noticed that in all the uses so far, we pipe the output of `CastaliaResults` to `CastaliaPlot` (using the unix '|' pipe). That is the normal/expected usage pattern. The table produced by `CastaliaResults` is drawn by `CastaliaPlot` according to some options. The default[6] rule that produces a graph from a text table is: The columns of the table determine the x axis coordinates and the values in the cells of the table are the y axis coordinates. So if a cell under column "rate=35" has a value 720 then a point will be drawn at (35, 720). If we have multiple rows they are drawn as multiple lines (or multiple bars) with different colours. The legend, the graph title, the x axis title and marks, and the y marks are determined automatically from the table info.

`CastaliaPlot` is using **gnuplot** to produce the graphs. Run `CasstaliaPlot` with –h to get all the options available.

```
$ CastaliaPlot -h
```

5 If you are unfamiliar with regex a good reference can be found in: http://www.regular-expressions.info/reference.html

6 In the previous section examples, CastaliaPlot used the –s stacked option which does not use the default rule. So do not get confused by the graphs in the previous section.

```
Usage: CastaliaPlot [options]

Options:
  -h, --help            show this help message and exit
  -d, --debug           Debug mode, will display gnuplot commands as they are
                        dispatched
  -g, --greyscale       Use greyscale colors only, negates effect of --colors
  -l LEGEND, --legend=LEGEND
                        Set legend position, default is 'top right', search
                        for gnuplot's 'set key' for all possible options
  -o FILE, --output=FILE
                        Select output file, default is 'plot.ps'
  -s STYLE, --style=STYLE
                        Plot style to be used, supported values: linespoints,
                        histogram, stacked
  --color-opacity=OPACITY
                        Set box colour opacity, default is 0.65
  --colors=COLORS       Specify a comma-seprated list of colors to be used in
                        the plot, or use '?' for full list available,
                        arbitrary RGB values are supported with #RRGGBB format
  --gnuplot=GNUPLOT     Path to gnuplot executable, default is 'gnuplot'
  --hist-box=BOXWIDTH   Set width of histogram columns
  --hist-gap=HISTGAP    Set gap between histogram columns
  --invert              Invert the table passed as input (i.e. make rows to be
                        columns and vice versa)
  --linewidth=LINEWIDTH
                        Set linewidth, only with linespoints style
  --order-columns=ORDER
                        A comma separated list of column indexes. Columns can
                        be reordered or skipped (NOTE: this is applied BEFORE
                        invert)
  --ratio=RATIO         Set aspect ratio of the graph
  --xrotate=ROTATE      Set xtics rotation, in degrees (e.g. 45)
  --xtitle=XTITLE       Set title of x-axis, will be determined automatically
                        by default
  --yrange=[MIN:]MAX    Set range of y-axis
  --ytitle=YTITLE       Set title of y-axis, not displayed by default
```

The most common switches used are `-o`, `-s` and `-l`. The first one gives the output file name. The suffix of the file name has a functional use: it decides the format of the image file. The default is postscript (`.ps`), and accepted suffixes are `.png`, `.gif`, `.jpg`. We recommend the png format for clearer images if you do not want to use ps.

The –s switch determines the style of the graph. There are 3 styles supported: Points joined with lines (`linespoints`), bars (`histogram`) and stacked bars (`stacked`). The

first and second options are quite similar in the sense that they operate with the default way (making columns the x axis and drawing other multiple lines or multiple bars for each row). Stacked is different. Rows are the x axis coordinates and columns are drawn as stacked bars for each row. This is particularly useful when we want to represent breakdowns, such as the MAC layer packet breakdown or the Radio layer packet breakdown.

The –l switch determines the position and other formatting options of the legend. The arguments are directly passed to gnuplot when setting the key properties (i.e legend properties). So whatever options gnuplot's `set key` takes, we allow. For instance, you can combine labels such as bottop/top/outside with left/right. Or you can also modify the width of the legend by `width NUM` (NUM is the number of characters). We find this useful when we draw the legend outside the graph area and the automatic legend width is too long, so we are adjusting it by reducing the width by some characters (look at the last graph example in the previous section).

Other interesting switches `are --colors`, where you determine manually the colours of the lines or bars (run `CastaliaPlot --colors ?` to get a list of supported colours and colour maps), `--invert` where you invert the table so that the rows become the columns, and `--order-columns`, where you explicitly give an order that you want the columns drawn (useful only in stacked style). We will see more examples of using `CastaliaPlot` in the sections to follow.

3.5 Advanced usage

Let us move to a different simulation scenario than the ones we have already seen. Go to `Castalia/Simulations/valuePropagation/` and examine the omnetpp.ini file there. It defines a grid of 4 nodes by 4 nodes (=16 nodes), uses a MAC called "TunableMAC" and an application called "valuePropagation". The application works in the following way: All nodes sample their temperature sensors periodically. If a sensed value is above the threshold of 15ºC then this value needs to be broadcasted. If a node receives this value from any other node it tries to broadcast it and then sets a flag that it has done its duty. Depending on the behaviour of the MAC and the condition of the channel between the nodes, the value is propagated in the network. The interesting thing to explore here is how the value propagation is affected by MAC parameters and how much energy is consumed each time. TunableMAC implements a generic duty cycle MAC, and as the name suggests, it has many parameters that the user can tune. With the current settings of the omnetpp.ini file, only node 0 is sampling a value beyond 15 (node 0 samples a value of 40 + noise), the rest are sampling a value of 0 + noise. So node 0 is the only source of the special value to be propagated. Notice that the omnetpp.ini file provides 3 main configurations (+3 more auxiliary configs):

```
[Config varyDutyCycle]
SN.node[*].Communication.MAC.dutyCycle = ${dutyCycle= 0.02, 0.05, 0.1}


[Config varyBeacon]
SN.node[*].Communication.MAC.beaconIntervalFraction = ${beaconFraction= 0.2,
0.5, 0.8}


[Config varyTxPower]
SN.node[*].Communication.Radio.TxOutputPower = ${TXpower="-1dBm","-5dBm"}
```

Each of the configurations varies a different parameter, so we can combine them all together with the `Castalia` script and have one big simulation that runs all 3×3×2 = 18 parameter possibilities:

```
valuePropagation$ Castalia -c varyDutyCycle,varyBeacon,varyTxPower
Running configuration 1/1
```

Let us check the resulting output file:

```
/valuePropagation$ CastaliaResults -i 100812-102156.txt
+---------------------+------------------+------------+
|              Module |           Output | Dimensions |
+---------------------+------------------+------------+
|         Application |        got value | 16x1       |
| Communication.Radio | RX pkt breakdown | 16x1(6)    |
|                     |        TXed pkts | 16x1       |
|     ResourceManager |  Consumed Energy | 16x1       |
+---------------------+------------------+------------+
NOTE: select from the available outputs using the -s option
```

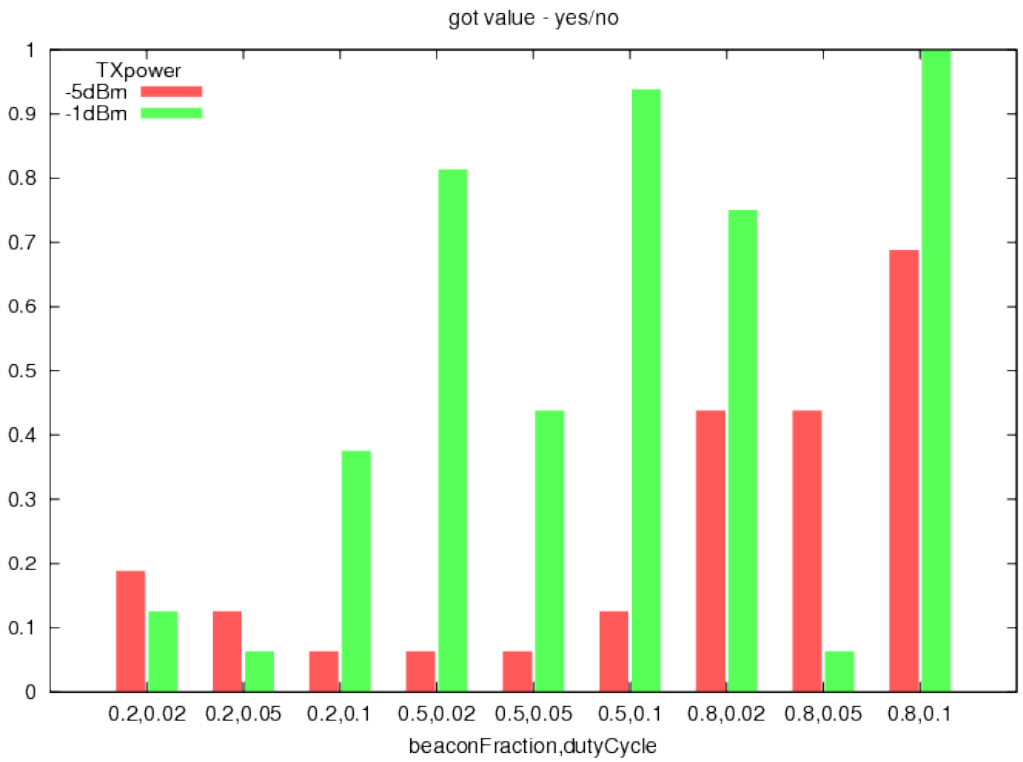
We see that the application module reports an output called “got value”. We also see that all of the 16 application modules (one for each node) have reported this output. This is a simple 1/0 output, reporting 1 if a node has a value above the threshold (either by sensing, or received by another node) and 0 if it is below the threshold. Looking at an average of this value across all sensor nodes, gives us the fraction of the nodes that have received the value. Thus this is a metric of value propagation. Let’s see the results:

```
/valuePropagation$ CastaliaResults -i 101223-162011.txt -s got
Application:got value
+----------------------------------+-----------------+-----------------+
|                                  | TXpower="-5dBm" | TXpower="-1dBm" |
+----------------------------------+-----------------+-----------------+
```

```
| beaconFraction=0.2,dutyCycle=0.02 | 0.188          | 0.125          |
| beaconFraction=0.2,dutyCycle=0.05 | 0.125          | 0.063          |
| beaconFraction=0.2,dutyCycle=0.1  | 0.063          | 0.375          |
| beaconFraction=0.5,dutyCycle=0.02 | 0.063          | 0.813          |
| beaconFraction=0.5,dutyCycle=0.05 | 0.063          | 0.438          |
| beaconFraction=0.5,dutyCycle=0.1  | 0.125          | 0.938          |
| beaconFraction=0.8,dutyCycle=0.02 | 0.438          | 0.75           |
| beaconFraction=0.8,dutyCycle=0.05 | 0.438          | 0.063          |
| beaconFraction=0.8,dutyCycle=0.1  | 0.688          | 1              |
+-----------------------------------+----------------+----------------+
```

The table shows the propagation metrics for all 18 different parameter scenarios. For example we see that when beaconFraction=0.2, dutyCycle=0.02, TXpower="-1dBm", 0.125 of the nodes (2/16nodes) got the value. For some cases with high beaconFraction value we see that all of the nodes got the value. How would we draw these results? The default way would produce 9 lines (since we have 9 rows in the table) each line having only two points (since we have only 2 columns). It would be nice if we could invert the table and have the rows as the x coordinates This can be done with CastaliaPlot's --invert switch.

```
valuePropagation$ CastaliaResults -i 101223-162011.txt -s got |
CastaliaPlot -o valueProp-1seed.png -s histogram --invert -l left
```



Notice how the graph title, the legend, the y axis marks, and the x axis title and marks are automatically determined by CastaliaPlot.

3.5.1 Manipulating the display of a results table

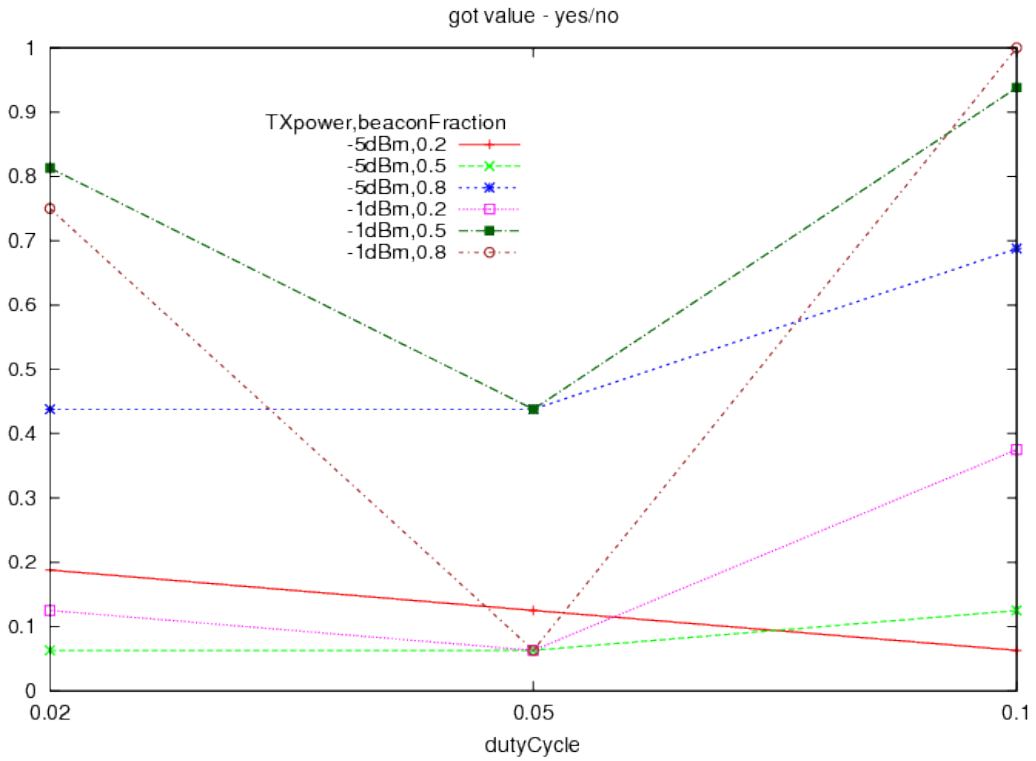
It is interesting to note here that there are 3 parameter dimensions in the results (beaconFraction, dutyCycle, TXpower) yet we can only show 2D tables. In the example above `CastaliaResults` has chosen to put TXPower in the columns and put beaconFraction in the "outer loop" of the rows enumeration. What if we wanted some other order in displaying the results? The user has full control with the `--order` switch. This switch is followed by a comma-separated list of labels. The first label will be the columns of the table, the second label will be the outer loop in the rows enumeration of the table and so on. You do not have to define all labels. If you define just one, this will be the columns and the rest will be ordered in a default way. Let's try this option:

```
/valuePropagation$ CastaliaResults -i 100812-102156.txt -s got --order=duty,TX


Application:got value
+---------------------------------+----------------+----------------+---------------+
|                                 | dutyCycle=0.02 | dutyCycle=0.05 | dutyCycle=0.1 |
+---------------------------------+----------------+----------------+---------------+
|TXpower="-5dBm",beaconFraction=0.2| 0.188          | 0.125          | 0.063         |
|TXpower="-5dBm",beaconFraction=0.5| 0.063          | 0.063          | 0.125         |
|TXpower="-5dBm",beaconFraction=0.8| 0.438          | 0.438          | 0.688         |
|TXpower="-1dBm",beaconFraction=0.2| 0.125          | 0.063          | 0.375         |
|TXpower="-1dBm",beaconFraction=0.5| 0.813          | 0.438          | 0.938         |
|TXpower="-1dBm",beaconFraction=0.8| 0.75           | 0.063          | 1             |
+---------------------------------+----------------+----------------+---------------+
```

Let's draw a graph based on the table above, using the default linespoints style.

```
valuePropagation$  CastaliaResults -i 101223-162011.txt -s got --
order=duty,TX | CastaliaPlot -o valueProp-reorder-1seed.png -l 1,0.9
```

The resulting graph is not very clear, since there are 6 curves with no specific trends and several overlapping points. The previous bar representation of the results is more clear (do not forget this is the same table that was ordered in a different way and drawn with lines instead of bars). Still we are showing the alternate version here to demonstrate the features of CastaliaResults and CastaliaPlot. Notice how the legend and axes are automatically adjusted. Also note the manual positioning of the legend at the point (1,0.9). Note what is the effect at the graph: The right top corner of the legend is placed at coordinates (0.05, 0,9). The points of the x axis are internally numbered 0,1,2,3,.. so 1 means the second tick mark which happens to be 0.05. You can use real numbers too. 0.5 means the middle between the first and second x tick mark. Y axis marks are represented as shown on the graph.



The `--order` switch is especially useful when we create graphs since the default mode of `CastaliaPlot` takes the values on the columns as the x axis values and the values in the cells as the y axis values. Thus by playing with the order that the dimensions are displayed in the text graph we are affecting the way the graph will be drawn.

If we use the `-n` switch then the resulting table will have a label (and dimension) named "node" and might also have a label (and dimension) named "index". These label names can also be used with the `--order` switch. If the `-n` is used, and no order is specified, the "node" label is used as the columns of the table by default.

For valuePropagation, executing `CastaliaResults` with the `-n` switch and showing the "got value" output means that we can see which individual node got the output and which did not. Let's try it (we will not show the results here since the lines get too wide to be shown properly, you are encouraged to try the commands though and see the results for yourself).

```
valuePropagation$ CastaliaResults -i 100812-102156.txt -s got -n -f -5dBm
```

Notice the use of the `–f` switch that filters the rows shown. In the example above only rows containing the string "-5dBm" will be shown (that is, 9 out of the 18 possible scenarios). You notice that the lines of the output are long, since we have 16 nodes (i.e. 16 columns to show). You can change the order that the dimensions are displayed, but this might not help a lot. You can also try the more compacted output format using the switch –o 2.

```
valuePropagation$ CastaliaResults -i 100812-102156.txt -s got -n -f -5dBm –o 2
```

The compacted output format is primarily used so you can easily copy the results table to an Excel spreadsheet (or other external program), and use the character '|' as the cell separator. Hopefully the existence of `CastaliaPlot` limits the need for graph productions by third party programs. However, you might still need to create some custom graphs that are not possible with `CastaliaPlot,` so the `-o 2` option offers an easy way to export results in a more compacted form.

What if we want to filter the rows even further? Say we want to have only rows that have beaconFraction=0.2 and TXPower=-5dBm. The `–f` switch and the right regular expression does the trick

```
valuePropagation$ CastaliaResults -i 100812-102156.txt -s got -n -f 0\.2.*-5dBm -o 2
```

So we gave the regular expression `0\.2.*-5dBm` which translates to: match any string that has 0.2 ('.' is a special character so we had to prefix it with '\') then has any number of characters (the '.*' part), and finally has the string '-5dBm'.

3.5.2 Multiple repetitions and confidence intervals

You probably noticed that the value propagation results we got from our valuePropagation simulations did not seem to have clear trends among the dimensions we used. The clearest trend is probably that increasing TXpower also increases value propagation. How about the other output of interest: Energy?

```
/valuePropagation$ CastaliaResults -i 100812-102156.txt -s energy
ResourceManager:Consumed Energy
+----------------------------------+-----------------+-----------------+
|                                  | TXpower="-5dBm" | TXpower="-1dBm" |
+----------------------------------+-----------------+-----------------+
| beaconFraction=0.2,dutyCycle=0.02 | 0.087           | 0.087           |
| beaconFraction=0.2,dutyCycle=0.05 | 0.104           | 0.104           |
| beaconFraction=0.2,dutyCycle=0.1  | 0.134           | 0.135           |
| beaconFraction=0.5,dutyCycle=0.02 | 0.089           | 0.103           |
| beaconFraction=0.5,dutyCycle=0.05 | 0.104           | 0.108           |
| beaconFraction=0.5,dutyCycle=0.1  | 0.135           | 0.138           |
| beaconFraction=0.8,dutyCycle=0.02 | 0.105           | 0.119           |
| beaconFraction=0.8,dutyCycle=0.05 | 0.11            | 0.106           |
| beaconFraction=0.8,dutyCycle=0.1  | 0.139           | 0.143           |
+----------------------------------+-----------------+-----------------+
```

Trends seem clearer here. But how do we improve the results for the value propagation? How do we get to see clear trends? The randomness of results implies randomness in the process that produced them. Indeed there are many random processes at play here: shadowing in the wireless channel, different start up times for the nodes, several

random decisions at the MAC. Castalia has 11 distinct random number streams that affect different parts of the simulation. As a user you probably want to run your simulations with more that one set of random seeds (i.e., more that one set of produced random number streams). We can very easily do this by using the `–r` switch followed by the number of repetitions we want to run (each repetition is run with a different set of random seeds). Let's run 3 repetitions of the simulation we tried before:

```
valuePropagation$ Castalia -c varyDutyCycle,varyBeacon,varyTxPower -r 3
```

Have a look at the results:

```
valuePropagation$ CastaliaResults -i 100812-132444.txt -s energy
ResourceManager:Consumed Energy
```

Energy results have not changed much compared to running just one simulation, but there are some cells that have changed considerably, notably the cases where beaconFraction=0.8,dutyCycle=0.02. How about the value propagation results?

```
/valuePropagation$ CastaliaResults -i 100812-132444.txt -s got
Application:got value
+-----------------------------------+-----------------+-----------------+
|                                   | TXpower="-5dBm" | TXpower="-1dBm" |
+-----------------------------------+-----------------+-----------------+
| beaconFraction=0.2,dutyCycle=0.02 | 0.087           | 0.087           |
| beaconFraction=0.2,dutyCycle=0.05 | 0.104           | 0.106           |
| beaconFraction=0.2,dutyCycle=0.1  | 0.135           | 0.135           |
| beaconFraction=0.5,dutyCycle=0.02 | 0.092           | 0.104           |
| beaconFraction=0.5,dutyCycle=0.05 | 0.107           | 0.109           |
| beaconFraction=0.5,dutyCycle=0.1  | 0.136           | 0.136           |
| beaconFraction=0.8,dutyCycle=0.02 | 0.092           | 0.116           |
| beaconFraction=0.8,dutyCycle=0.05 | 0.112           | 0.122           |
| beaconFraction=0.8,dutyCycle=0.1  | 0.136           | 0.143           |
+-----------------------------------+-----------------+-----------------+
```

The results are quite different compared to the ones when we executed only one simulation. Another thing to notice is that the results are "smoother"; there is less extreme variation. Are 3 repetitions enough though? We do not want to run too many repetitions since simulation will take longer to complete, but how do we know a certain number is enough? We can use statistical tools to answer this question. More specifically we can instruct CastaliaResults to calculate the confidence intervals of the results over the repetitions it executed. To do that, we use the –c switch ('c' standing for 'confidence'), giving it the confidence level (level given as a percentage) we want our intervals calculated for:

```
valuePropagation$ CastaliaResults -i 100812-132444.txt -s got -c 95
Application:got value
(got value table omitted for brevity, only confidence intervals table shown)
+-----------------------------------+-----------------+-----------------+
Application:got value - confidence intervals
+-----------------------------------+-----------------+-----------------+
|                                   | TXpower="-5dBm" | TXpower="-1dBm" |
+-----------------------------------+-----------------+-----------------+
| beaconFraction=0.2,dutyCycle=0.02 | 0.015           | 0.014           |
| beaconFraction=0.2,dutyCycle=0.05 | 0.013           | 0.019           |
| beaconFraction=0.2,dutyCycle=0.1  | 0.014           | 0.015           |
| beaconFraction=0.5,dutyCycle=0.02 | 0.018           | 0.014           |
| beaconFraction=0.5,dutyCycle=0.05 | 0.02            | 0.02            |
| beaconFraction=0.5,dutyCycle=0.1  | 0.02            | 0.02            |
| beaconFraction=0.8,dutyCycle=0.02 | 0.016           | 0.02            |
| beaconFraction=0.8,dutyCycle=0.05 | 0.021           | 0.008           |
| beaconFraction=0.8,dutyCycle=0.1  | 0.019           | 0               |
+-----------------------------------+-----------------+-----------------+
```

A 95% confidence interval CI, means that the true average of the quantity we are seeking, lies within the span [sample_average-CI .. sample_average+CI] for 95% of the possible sample sets chosen. Confidence intervals have some fine notions in their definitions so it is wise you read some reference material about them[7]. For example, it is worth noting that the confidence intervals are valuable when the statistical model we are assuming is true. In our case there is the assumption that the samples are following a Gaussian distribution. This might not be true in many cases and it is actually not the case here (more on this later). Also an outlier can significantly change the average without worsening/increasing the confidence interval by much, so it is not an indication that the results are correct in any way. It is just an indication of whether we have had enough samples (enough repetitions) from that sample set to tightly determine a “true” average given that our statistical assumptions are correct.

There are other ways to look at variability of results. `CastaliaResults` also supports calculation of variability intervals for arbitrary variability levels VL. A variability interval (for variability level VL) is the tightest interval that includes VL% of the samples. It can give you an indication of where most of the values are, and how they relate to the average (you might for example see biases compared to the average). Let’s look at the variability intervals for value propagation:

```
valuePropagation$  CastaliaResults -i 101223-181746.txt -s got -v 95
```

7 The Wikipedia article contains enough information and gives a good explanation of fine notions distinctions: http://en.wikipedia.org/wiki/Confidence_interval

```
Application:got value - yes/no
+-----------------------------------+-----------------+-----------------+
|                                   | TXpower="-5dBm" | TXpower="-1dBm" |
+-----------------------------------+-----------------+-----------------+
| beaconFraction=0.2,dutyCycle=0.02 | 0.167           | 0.125           |
| beaconFraction=0.2,dutyCycle=0.05 | 0.104           | 0.333           |
| beaconFraction=0.2,dutyCycle=0.1  | 0.125           | 0.167           |
| beaconFraction=0.5,dutyCycle=0.02 | 0.271           | 0.875           |
| beaconFraction=0.5,dutyCycle=0.05 | 0.396           | 0.604           |
| beaconFraction=0.5,dutyCycle=0.1  | 0.417           | 0.604           |
| beaconFraction=0.8,dutyCycle=0.02 | 0.188           | 0.625           |
| beaconFraction=0.8,dutyCycle=0.05 | 0.542           | 0.958           |
| beaconFraction=0.8,dutyCycle=0.1  | 0.313           | 1               |
+-----------------------------------+-----------------+-----------------+
Application:got value - variability intervals
+-----------------------------------+-----------------+-----------------+
|                                   | TXpower="-5dBm" | TXpower="-1dBm" |
+-----------------------------------+-----------------+-----------------+
| beaconFraction=0.2,dutyCycle=0.02 | 0:1             | 0:1             |
| beaconFraction=0.2,dutyCycle=0.05 | 0:1             | 0:1             |
| beaconFraction=0.2,dutyCycle=0.1  | 0:1             | 0:1             |
| beaconFraction=0.5,dutyCycle=0.02 | 0:1             | 0:1             |
| beaconFraction=0.5,dutyCycle=0.05 | 0:1             | 0:1             |
| beaconFraction=0.5,dutyCycle=0.1  | 0:1             | 0:1             |
| beaconFraction=0.8,dutyCycle=0.02 | 0:1             | 0:1             |
| beaconFraction=0.8,dutyCycle=0.05 | 0:1             | 1:1             |
| beaconFraction=0.8,dutyCycle=0.1  | 0:1             | 1:1             |
+-----------------------------------+-----------------+-----------------+
```

We notice that the intervals reported are either the whole interval [0..1] or just [1..1]. This is somewhat strange and not very helpful in our particular case. This happens because of what we consider samples. Samples are individual reports from nodes, so for the value propagation case these are either 0 or 1 (got the value or not, no other value in between). They are not the averages from the all the nodes for a particular seed set. For our particular case this is not very useful, but we wanted to highlight it here so the user can be aware of the limitations of these statistical tools. This also means that the samples we are getting are not normally distributed so we should not put too much confidence on the confidence intervals reported either (pardon the pun). It is actually hard to determine how many seeds are enough in this scenario. We can keep increasing the number of repetitions and manually inspect how the averages are changing. Fifteen seeds seem enough with this procedure, but we want to remind you that this does not guarantee any correctness of results. We might have outliers in the sample sets caused by bugs in the application/protocol that manifest themselves

statistically. It is crucial to run our simulation over multiple seed sets and inspect the results for irregularities. Yet another switch we can use is `--all` that shows all samples for every seed. Again in this case we will have either 0 or 1, but in other scenarios it can show us outliers easily and we can investigate these cases further. In the future we might provide more options of calculating confidence intervals (e.g., taking averages across nodes to be individual samples and not just per node output be considered as individual samples)

If the confidence levels, or variability levels, or all samples are enabled by CastaliaResults and passed to CastaliaPlot then they are drawn automatically in the graph. We will see some examples of this in the next section.

Checking the results of our simulation scenario under multiple seed sets, and executing more repetitions if needed, is a crucial part of simulation. Finally, we remind you that when we execute `CastaliaResults` with no arguments and we see the configurations of the different results files in the directory, the number of different seed runs (i.e. number of repetitions) appears in a parenthesis next to the configuration run.

3.5.3 Changing configurations at command line

You have probably noticed that often, configurations set only one parameter. For example, in valuePropagation all 3 configurations we used and combined (i.e., varyDutyCycle, varyBeacon, varyTxPower) set only the duty cycle, the beacons length, and the TX power respectively. Sometimes we wish to change this single parameter to a different value (or different range of values) to check something quickly. We can create a new configuration setting the new value, but usually we just add a new line setting the new value and we comment out the old one. This is a bad practice because we are losing the connection between what the name of the config is and what it actually does (it depends on what was commented out or not, which we do not automatically know). Since Castalia 3.1 we have a better and easier way to deal with this situation. If a configuration is setting a single parameter we can redefine it at command line and this information is kept in the output results file. For example we can type:

```
valuePropagation$ Castalia -c varyDutyCycle=0.03
```

This will set the single variable of the configuration varyDutyCycle (i.e., `SN.node[*].Communication.MAC.dutyCycle`) to 0.03. We can use whatever expression we would use in a configuration file. For example we can assign a range of values. Be careful though whenever you use the characters ‘$’, ‘{‘, ‘}’in the command line, since these characters are usually interpreted by most command line shell environment (e.g. bash expects to find the name of an environment variable after it). If we want to pass these

characters, along with the rest of the string to be parsed by the Castalia script, we just need to prefix them with the character '\'. So we could type:

```
valuePropagation$ Castalia -c varyDutyCycle=\$\{dytyCycle=0.03,0.035,0.04\}
```

This will have the following equivalent effect:

```
SN.node[*].Communication.MAC.dutyCycle =
                                    ${dutyCycle=0.03,0.035,0.04}
```

You can combine configurations as always.

```
$Castalia –c varyDutyCycle=\$\{dutyCy=0.06,0.08\},varyBeacon=1.0,varyTxPower
Running configuration 1/1

valuePropagation$ CastaliaResults
Castalia output files in current directory:
+------------------+-------------------------------------------+------------------+
|                  | Configuration                             |     Date         |
+------------------+-------------------------------------------+------------------+
| 110214-174617.txt | varyDutyCycle=${dutyCy=0.06,0.08},       | 2011-02-14 17:46 |
                                  varyBeacon=1.0,varyTxPower (1)
```

3.6 Complex simulation examples

We have seen all the basic tools to run simulations, review the results, and create graphs from the results. We have also seen some non-trivial examples that showcased several concepts of the `Castalia`, `CastaliaResults`, and `CastaliaPlot` scripts. Let us now see some examples taken from real simulation needs. Hopefully this will give you a deeper understanding of the simulation cycle and the usage of Castalia. The first simulation scenario is from a Body Area Network using 802.15.4 MAC. We check performance under different MAC functionalities and wireless channel conditions. The second scenario is a WSN deployed on a bridge. We check the packet delivery ratio under different MACs and different bridge sizes.

3.6.1 Body Area Network simulation example

Go `to Simulations/BANtest/` and open omnetpp.ini, a large configuration file (having 20 Config sections) that is used to simulate a variety of scenarios to evaluate MACs in Body Area Networks. In the General section you can see that we are using a custom pathLoss map. This map is derived from our experimental measurements and defined in a file `pathLossMap.txt` We also use a file to define the temporal variation of the wireless channel also derived from our measurement campaigns (section 4.1 provides more details about the format and meaning of these files).

All scenarios use the `throughputTest` application, where all nodes send packets to a sink/hub node at a constant (configurable) rate. The hub is node 0. Have a look at the summary of the configurations:

```
Castalia/Simulations/BANtest$ Castalia
List of available input files and configurations:
* omnetpp.ini
        General
        ZigBeeMAC
        GTSon
        GTSoff
        noTemporal
        BaselineMAC
        pollingON
        pollingOFF
        naivePolling
        minScheduled
        maxScheduled
        varyScheduled
        varyRAPlength
        oneNodeVaryRate
        oneNodeVaryPower
        oneNodeVaryTxNum
        allNodesVaryRate
        setRate
        setPower
        allNodesVaryPower
        varyReTxNum
```

You can see that there are two basic MACs: Zigbee and BaselineMAC. We can vary the packet rate, the Tx power, the retransmission attempts, in one node or all the nodes. We can vary parameters of the MACs relating to scheduled access, random access and improvised access (polling). We can also choose a wireless channel with no temporal effects.

For the example in this section we will concentrate on ZigbeeMAC (or more accurately IEEE 802.15.4 MAC). Let's run a simulation testing how Zigbee performs when its Guaranteed Time Slot (GTS)[8] functionality is turned on or off and also when we are

8 GTS is a TDMA-based scheme that 802.15.4 is using. In our particular simulation scenario, each round has 16 slots. Each of the 5 nodes is requesting and getting 3 slots, thus 15 slots in total are devoted to TDMA. The remaining slot is always the first slot after the beacon, and is using a contention

having a wireless channel that exhibits temporal pathloss variation vs. one that it does not[9]. For all of these 4 scenarios we will vary the packet rate of the sending nodes. We also run every scenario with 5 different seed sets.

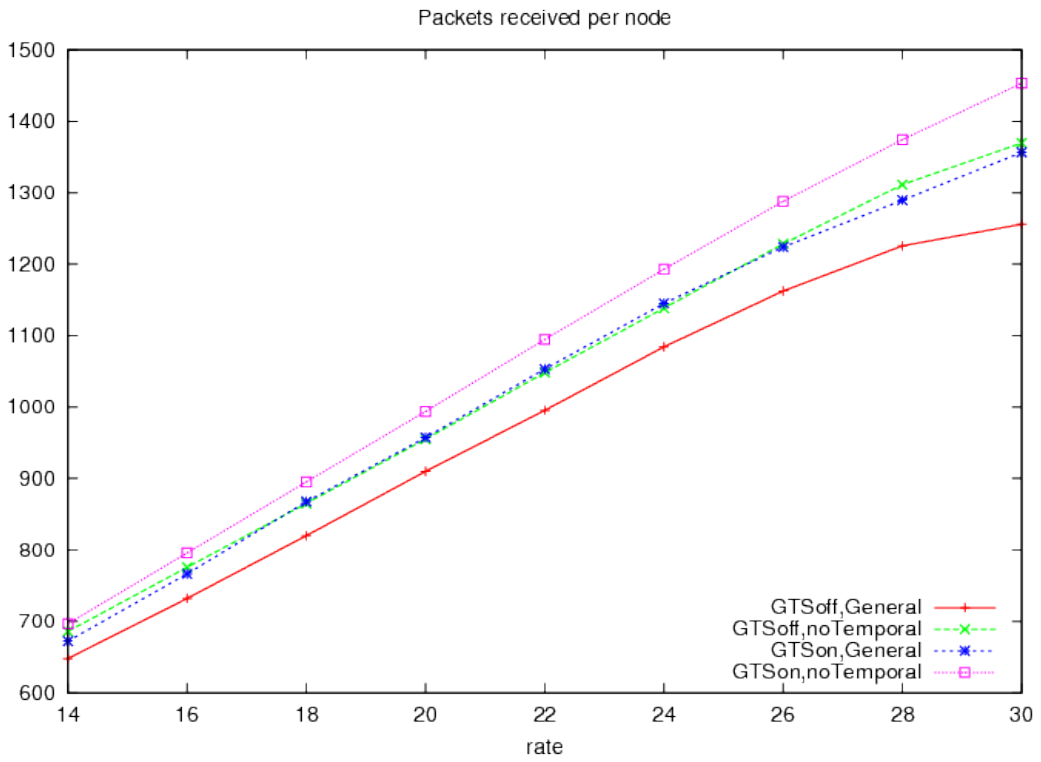
```
BANtest$ Castalia -c ZigBeeMAC,allNodesVaryRate,[GTSon,GTSoff]
[noTemporal,General] -r 5
Running configuration 1/4
Running configuration 2/4
Running configuration 3/4
Running configuration 4/4
BANtest$ CastaliaResults -i 101221-191001.txt
+------------------+---------------------------------------+------------+
|            Module |                                Output | Dimensions |
+------------------+---------------------------------------+------------+
|       Application |        Application level latency, in ms | 1x1(31)    |
|                   |              Packets received per node | 1x5        |
| Communication.MAC | Fraction of time without PAN connection | 5x1        |
|                   |             Number of beacons received | 5x1        |
|                   |                 Number of beacons sent | 1x1        |
|                   |                       Packet breakdown | 5x1(5)     |
|Communication.Radio |                       RX pkt breakdown | 6x1(5)     |
|                   |                              TXed pkts | 6x1        |
|   ResourceManager |                         Consumed Energy | 6x1        |
|   wirelessChannel |                Fade depth distribution | 1x1(14)    |
+------------------+---------------------------------------+------------+
```

We see the rich output produced by the simulation. Let’s look at the packets received by the application (and let’s draw a graph since text would be too hard to follow):

```
/BANtest$ CastaliaResults -i 101221-191001.txt -s packets |
CastaliaPlot -o zigbee-ban-app-4types.png -l bottom
```

based scheme. When GTS is off then all 16 slots are using contention-based access.

9 The General configuration describes a wireless channel with temporal variability so we are using “General” config to describe a temporal channel (vs. the noTemporal config which describes a non temporal channel)

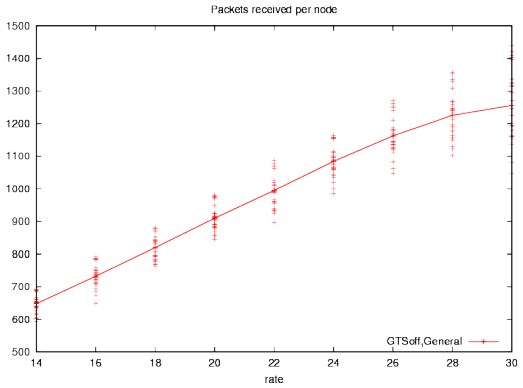


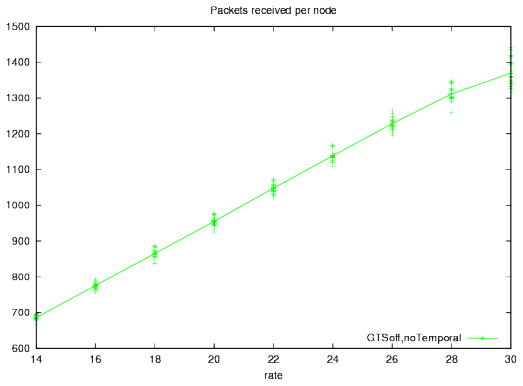
The y axis is average packers received per node (only node 0 receives packets but it receives them from multiple nodes, this is what the "per node" means). The x axis is the sending rate for each node measured in packets/sec. Nodes are sending packets for 50 secs so if we had perfect reception we would reach 1500 packets per node for the 30packets/sec/node case. Notice that for low traffic the GTSon noTemporal curve achieves the maximum (e.g., 16packets/sec/node → 800packets received per node). Generally the protocol performs better when the GTS is turned on. This is something to be expected as TDMA schemes make a more efficient use of the wireless medium and are reducing interference. We also notice that the performance (packets received) is better when the channel has no temporal variation. Again this is to be expected as the temporal variation introduces some deep fades that break the connectivity between the sender nodes and the hub, whereas with the no temporal pathloss variation the links are kept in a relatively good state for our specific example. Finally notice that as the traffic rate reaches the larger volumes we start seeing early indications of saturation, especially for the GTSoff General case.

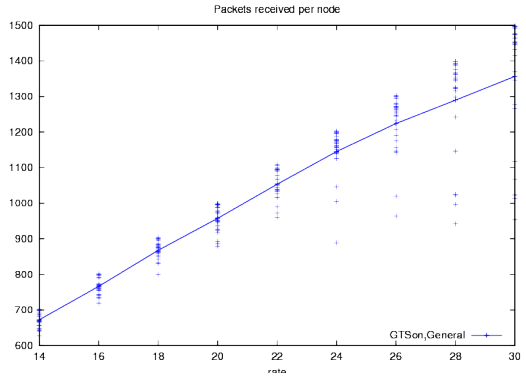
We run the scenarios for 5 seed sets. The confidence levels calculated are quite tight but it would be good to see the variability of results and investigate how reasonable they look. For that reason we use the --all switch and draw the four individual curves.

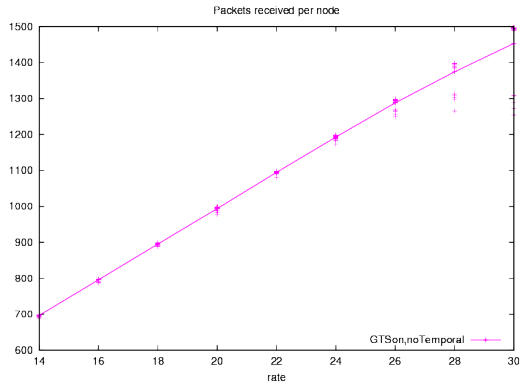
```
BANtest$ CastaliaResults -i 101221-191001.txt -s packets --all -f
"GTSoff,General" | CastaliaPlot -o zigbee-ban-app-GTSoff,General.png
-l bottom --colors r
```

```
/BANtest$ CastaliaResults -i 101221-191001.txt -s packets --all -f "GTSoff,noTemporal" | CastaliaPlot -o zigbee-ban-app-GTSoffno,Temporal.png -l bottom --colors g

BANtest$ CastaliaResults -i 101221-191001.txt -s packets --all -f "GTSon,General" | CastaliaPlot -o zigbee-ban-app-GTSon,General.png -l bottom --colors b

BANtest$ CastaliaResults -i 101221-191001.txt -s packets --all -f "GTSon,noTemporal" | CastaliaPlot -o zigbee-ban-app-GTSon,noTemporal.png -l bottom --colors m
```


Packets received per node
1500
1400
1300
1200
1100
1000
900
800
700
600
500
14
16
18
20
22
24
26
28
30
rate
GTSoff,General

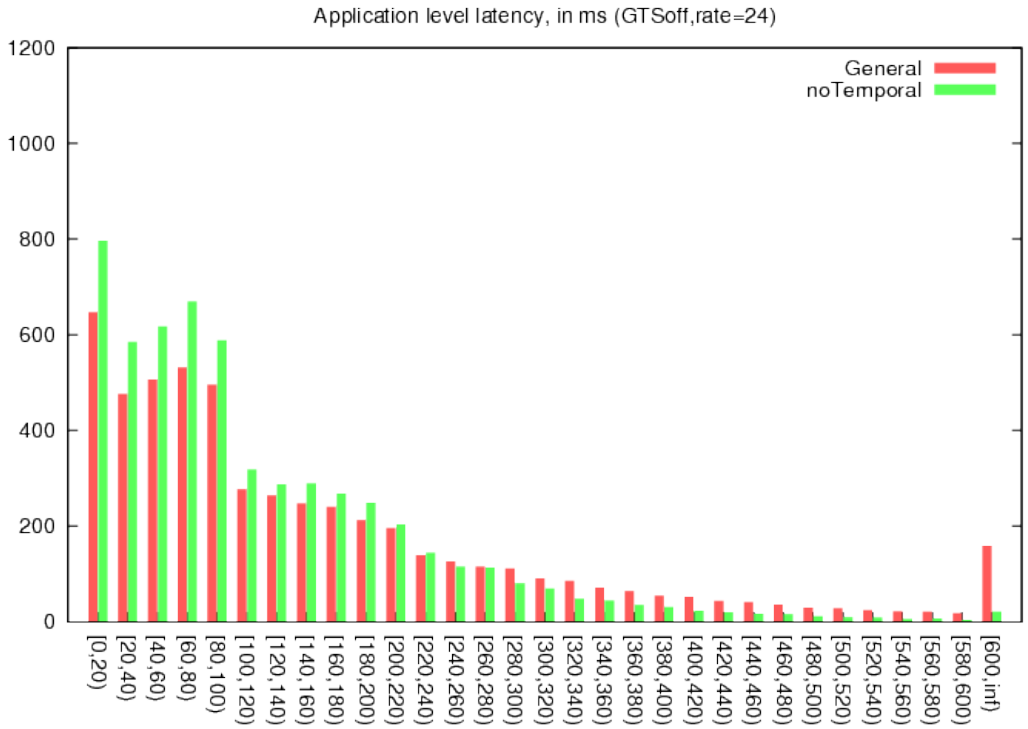

Packets received per node
1500
1400
1300
1200
1100
1000
900
800
700
600
14
16
18
20
22
24
26
28
30
rate
GTSoff,noTemporal



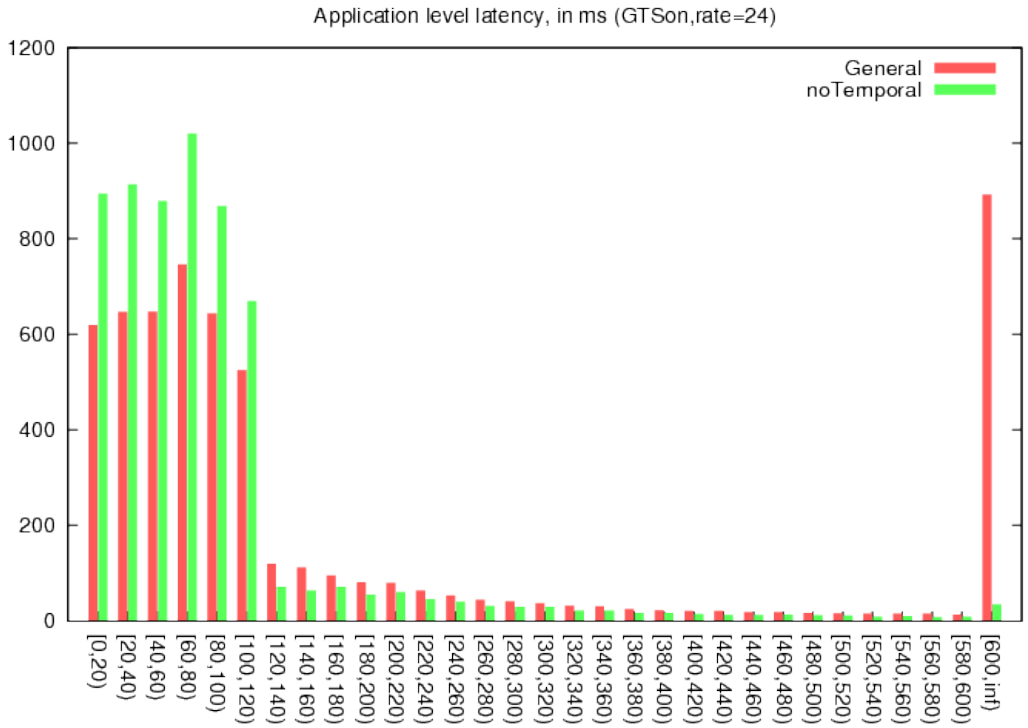


There is some variability of results. Remember each point is a result from an individual seed set but also from an individual node, and since the nodes have different path losses to the hub (due to the use of our experimental pathloss map) we can expect different performances from different nodes. This is especially true when we have temporal variation and these path losses differences manifest themselves as different probabilities of link outages. Generally the variability appears reasonable, with the possible exception of a few low points at high rates in GTSon,General. We can delve into the different aspects of the results to try and explain the full behaviour and at the end we can consult individual run traces. Let us start by looking at the application-level latency histograms for some cases:

```
BANtest$ CastaliaResults -i 101221-191001.txt -s latency -f
GTSoff.*=24 | CastaliaPlot -o zigbee-ban-app-latency-GTSoff.png --
yrange 1200 --xrotate 90 -s histogram
```




```
BANtest$ CastaliaResults -i 101221-191001.txt -s latency -f
GTSon.*=24 | CastaliaPlot -o zigbee-ban-app-latency-GTSon.png --
yrange 1200 --xrotate 90 -s histogram
```



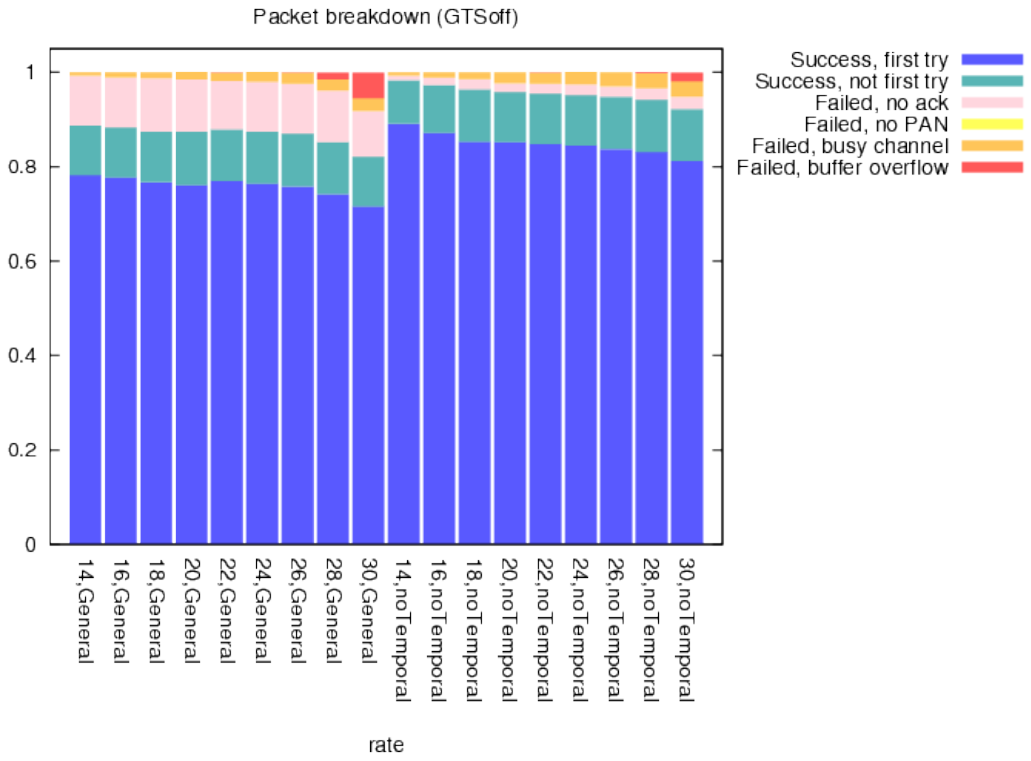
For the first graph (GTSoff, i.e. only contention-based access) we can see that most of the packets are received with under 100msecs latency, which means that they are transmitted in the first MAC frame after their creation (for this particular BAN simulation scenario we

have chosen the MAC frame to be 120ms). We also see that no temporal is performing better as expected. The non-negligible portion of packets at the [600..inf) bucket is a sign of oncoming saturation for the temporal case (General). For the second graph (GTSon) we see even more pronounced effects. The majority of the packets are received within the first frame of creation and we also see a big portion of packets with large delay. This tells us that there is potential saturation in this case, with overflown buffers, possibly explaining some of the low performance points in the "packets received per node" graph.

To further investigate we can look at the breakdown of packets at the MAC level:

```
BANtest$ CastaliaResults -i 101221-191001.txt -s "Packet break" -f
GTSoff -p | CastaliaPlot -o zigbee-ban-mac-GTSoff-percentage.png -s
stacked --colors b,dc,pi,y,o,r -l "outside width -7" --xrotate 90 --
order-columns=5,6,4,3,2,1 --yrange 1.05
```

This is a nice example of using CastaliaResutls and CastaliaPlot to achieve an elegant and informative graph. Notice how we show the results that match "Packet break", how we filter to show only rows with "GTSoff" and how we the results are shown as fractions of 1 (-p option). Notice also we choose the colors and reorder the columns to get the aesthetic result we wish.

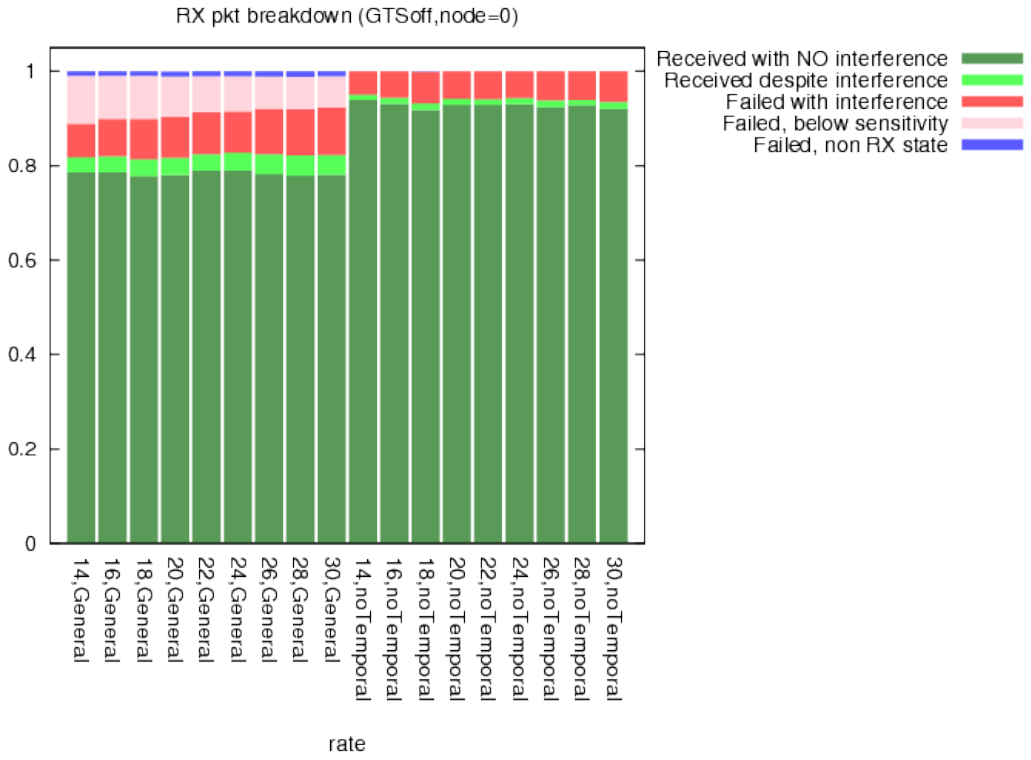


Looking at the graph we can get an immediate feeling on how better the noTemporal case is. We also see that the main difference is a portion of the packets who failed because of no Ack was received (a direct result of the deep fades in the channel and loss of connectivity). For high rates we also see more packets being overflown. This breakdown is for packets *sent at*

the MAC level. We can also look at the breakdown of packets *received at the Radio layer* of node 0 (the hub).

```
BANtest$ CastaliaResults -i 101221-191001.txt -s RX -f GTSoff.*node=0
-p -n | CastaliaPlot -o zigbee-ban-radio0-GTSoff-percentage.png -s
stacked -l "outside width-7" --yrange 1.05 --order-columns 5,4,1,2,3
--colors dg,g,r,pi,b --xrotate 90
```

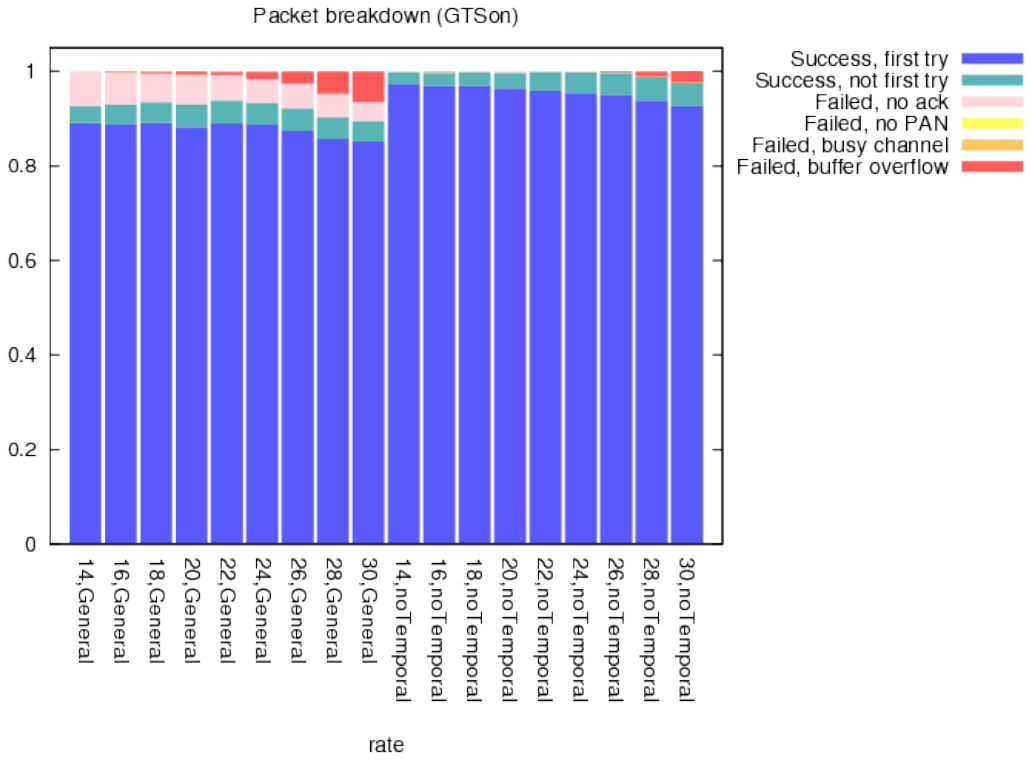
Notice how we are have to break the results per node (using –n) to get the radio layer of just node 0 and the more advanced filtering we do.



The graph verifies our assumptions for the cause of noAck packets from the previous graph. Although the packets that are interfered do not increase much in the General (i.e. temporal) case, we see a portion of packets failing due to very low received signal. This category does not even exist in the noTemporal case. We also see a small portion of packets that fail due to radio of node 0 being in the wrong state. In our particular case this can only mean that the radio is TXing yet the carrier sensing mechanism in other nodes is not effective. This hypothesis needs to be confirmed by looking at the traces.

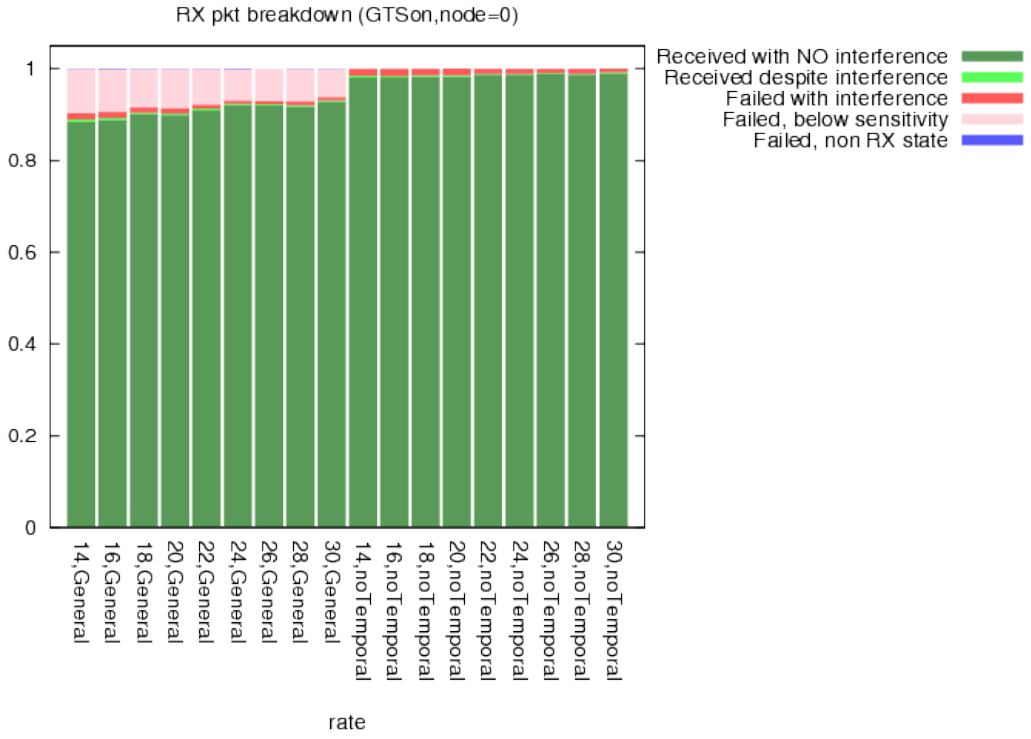
Let us look also at the GTSon case (TDMA-based access) too:

```
BANtest$ CastaliaResults -i 101221-191001.txt -s "Packet break" -f
GTSon -p | CastaliaPlot -o zigbee-ban-mac-GTSon-percentage.png -s
stacked --colors b,dc,pi,y,o,r -l "outside width -7" --xrotate 90 --
order-columns=5,6,4,3,2,1 --yrange 1.05
```



As expected we see that there are no packets that fail because the channel is found busy (since we are not working with contention-based access). It is very interesting to see that there are considerably more packets overflown for the General case compared to the results when GTSoff. This also agrees with our observations on latency graphs.

Finally the radio break down graph shows that we have much less interference now and the major fail packet category is packets with very low signal.



3.6.2 Bridge Test simulation example

This simulation scenario was created to test some basic aspects of a WSN used for structural health monitoring of a bridge. It has the following characteristics:

The sensing nodes are placed in a grid throughout the simulation field within 20 meters from each other. The sink node is located in the middle of the field, and all sensing nodes will try to deliver their reports to the sink. Every 5 minute (on average) a car appears in the simulation field (CarsPhysicalProcess is used, which creates objects moving in lines). A passing car is guaranteed to trigger all sensing nodes along its path, thus creating a traffic flow towards the sink node in the network. But not all nodes are triggered for the same amount of time; node on the central line of the deck spend more time above the triggering threshold. Additionally, the sink node will be distributing several packets [totalling 5Kbytes] to all sensing nodes at the beginning of the simulation and then repeat doing so every day of the simulation. These packets symbolize an update software patch.

The goal of this scenario is to evaluate the performance of such WSN with different parameters in MAC and Routing layers, as well as different sizes of the bridge being monitored. In release 3.1, the results from the BridgeTest simulation scenario are not very exciting since we are missing crucial routing functionality. The old tree-based routing present in version 2.3b is no longer available and the multipathRings routing does not seem to perform well. Thus we are simply using noRouting (some sort of app level broadcast is performed to dispense the results). The simulation scenario is interesting though because of the way we define different network sizes (according to the bridge size).

Open the omnetpp.ini file and look at the configurations. Notice how we are creating the various deployments for different bridge sizes:

```
[Config 100mBridge]
SN.field_x = 100
SN.field_y = 20
SN.deployment = "[0]->center;[1..18]->6x3"
SN.numNodes = 19

SN.physicalProcess[0].point1_x_coord = 0
SN.physicalProcess[0].point1_y_coord = 10
SN.physicalProcess[0].point2_x_coord = 100
SN.physicalProcess[0].point2_y_coord = 10
```

We have to set the correct field size, the correct number of nodes, and the correct deployment (proper grid size). Node 0 (the sink) always goes at the centre. Then we need

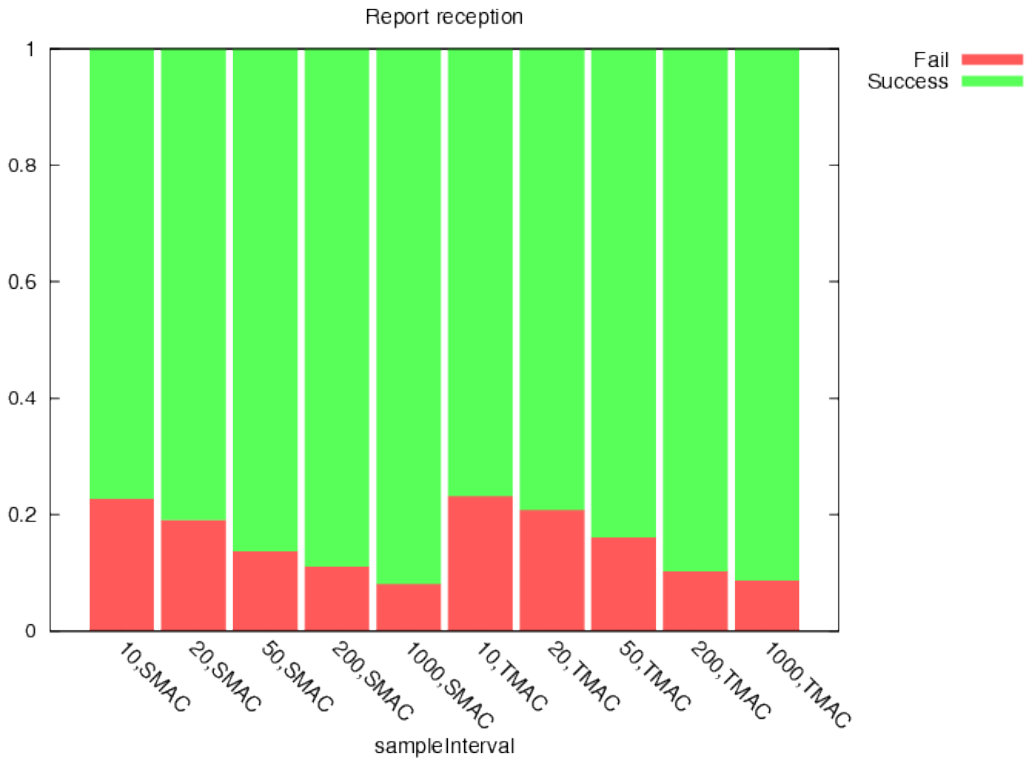
update certain parameters of the CarsPhysicalProcess so that it affects the whole span of the bridge.

We can then run a simulation on the 100m bridge testing two MAC protocols like so:

```
BridgeTest$ Castalia –c 100mBridge,varySampleRate,noRouting[SMAC,TMAC] -r 5
Running configuration 1/2
Running configuration 2/2
```

We can have a look at the breakdown of the report packets reaching the sink

```
BridgeTest$ CastaliaResults -i 110106-172853.txt -s report -p |
CastaliaPlot -o bridge-report.png -s stacked --xrotate 45 -l outside
```



The results show a very similar performance for SMAC and TMAC. Successes are proportionally more when we are using a bigger sampling interval (smaller sampling rate) as expected.

4 Modeling in Castalia

This chapter explains how Castalia models the different aspects of a wireless sensor network from communications to physical process. It also gives a detailed account of all the non-composite modules and their parameters. This chapter is your reference to understand how to use the different modules and what you can do with them. The single common thing that we can mention for all non-composite modules in Castalia is that they all have a parameter called `collectTraceInfo`. This is set by default to 'false'. If set to 'true', the module will produce trace information that will be written in the Castalia-Trace.txt file. We have already seen examples of this in Chapter 3.

Communications is the most carefully modeled aspect of the Castalia simulator. From the wireless channel to the radio behavior and the implementation of different MAC protocols, we tried to capture the essence and many details of their real counterparts.

4.1 The Wireless Channel

The wireless channel is a notoriously difficult medium to model, especially when taking into account mobile nodes, a changing environment (e.g., in the BAN case: the body moving) and broadband communications. Even though there is a big corpus of theoretical results and experimental measurements for wireless communication in general, they tend to practically affect areas with more commercial impact such as cellular communication, and recently WiMAX. The mobile ad hoc networks and wireless sensor networks have not gained as much from the modeling advances of wireless communication. There are multiple reasons for this, the main ones being: 1) more complicated problem, 2) comparatively smaller immediate tangible commercial benefits to allow for the expensive and tedious job of detailed measurements and modeling, and 3) researchers coming mostly from the CS, networking background, lacking deep knowledge and interest in the physical layer. Nevertheless, some researchers in the community have taken up the much needed role and have produced models that fit experimental data, at least for some important aspects. The recent interest with Body Area Networks and the upcoming IEEE BAN standard has created another important momentum. For example, at NICTA, we have created experimental testbeds to capture hundreds of thousands measurements. Those measurements are analyzed to provide accurate models for both the average path losses around the body, and more importantly, the temporal variation behaviour of the channel.

We are confident to claim that, concerning the wireless channel, Castalia is the most realistic simulator one could find for WSN and BAN. The word "realistic" here is used in the sense that the simulator is making the necessary provisions to capture various important

features of the wireless channel. In order to have results that accurately reflect reality one would need appropriate input parameters and input files. In simple words, one needs to "tune" the simulator right. In the simulation examples provided with the distribution of Castalia, many of the parameters are set at reasonable values that reflect some real situation, some though –especially large input files modeling temporal variation– are not freely available and are NICTA's intellectual property. NICTA is interested in various forms of collaboration, so you are welcome to contact us regarding more accurate input files.

4.1.1 Average path loss modeling

One important aspect of the wireless channel modeling is to estimate the average path loss between two nodes, or in general, two points in space. For WSN, where the separation of nodes is from a couple of meters to a hundred meters, the lognormal shadowing model has been shown[10] to give accurate estimates for average path loss. This is the formula that returns path loss in dB as a function of the distance between two nodes and a few parameters

$$PL(d) = PL(d_0) + 10 \cdot \eta \cdot \log\left(\frac{d}{d_0}\right) + X_\sigma$$

PL(d) is the path loss at distance d, ***PL(d_0)*** is the known path loss at a reference distance ***d_0***, ***η*** is the path loss exponent, and X_σ is a gaussian zero-mean random variable with standard deviation ***σ***. The four parameters in italics and bold, are defined as parameters of the wireless channel module. Looking into src`/wirelessChannel/WirelessChannel.ned`

```
double pathLossExponent = default (2.4);
double PLd0 = default (55);
double d0 = default (1.0);
double sigma = default (4.0);
```

To access these parameters in an .ini file you have to prefix their name with "`SN.wirelessChannel.`"

The lognormal shadowing model is not very accurate if you want to capture the correlation between the two directions of a link[11]. If you treat the two directions as independent links, the variance you get is much larger than the one experienced in reality. For this reason we are using the model to return an average path loss for *both* directions of a link and then we add and subtract *a separate* Gaussian zero-mean random variable with standard deviation `SN.wirelessChannel.bidirectionalSigma`. This standard

10 Zuniga et. al. [4] have shown that the observed Packet Reception Rates (PRR) in experimental setups with mica2 motes can be explained with the lognormal shadowing channel model **and** appropriate models for the radio modulation (which Castalia uses).

11 A link here is just a pair of nodes or more generally two points in space.

deviation should generally be small (default = 1.0). This parameter replaces the old parameter SN.wirelessChannel.allBidirectionalLinks, which was a much coarser attempt to capture correlation between the two directions of a link. Now, with the new parameter we have a more clean and independent way to control correlation between the two directions.

If we are concerned with BAN modeling, the lognormal shadowing model does not produce good results. In this case, we can use another option that Castalia gives us and that is to explicitly set our path loss map. For example, we might have measured average path losses using a testbed (as we do at NICTA) and provide these as input to Castalia. This is done through the `SN.wirelessChannel.pathLossMapFile` parameter which gives the filename of the specially formatted input file.

The input file has lines of the following format:

`TxNodeID>RxNodeID1:dB_value,RxNodeID2:dB_value,…`
example: `0>1:56,2:40,3:59,4:54,5:58`

This means that when node 0 is transmitting, node 1 is experiencing 56dB path loss, node 2 is experiencing 40dB loss, node 3 a 59dBm loss, etc.

Before Castalia 3.0 we also provided another option: to give a map of packet reception probabilities (also called packet reception rates: PRR) using the `SN.wirelessChannel.PRRMapFile` parameter. This is no longer an option because of changes in the radio model. Now the radio can dynamically change its modulation type, plus we can have multiple kids of radios operating in a network. To translate a PRR to a path loss in dB, you need to know the operation parameters of the radios involved. If you can have different and dynamically changing radio operating parameters it makes little sense to determine a wireless channel with a PRR map. Thus, the `PRRMapFile` parameter is now obsolete.

4.1.2 Allowing for node mobility

Allowing for mobile nodes, complicates matters, since now it is not enough to take the average path losses between the nodes. We need to keep state about path losses between points in the space. This implies that we need to break up the space in discrete cells and calculate the path losses from each cell to each other cell. Look at figure 4 for an example of such a map only for one transmitting cell.

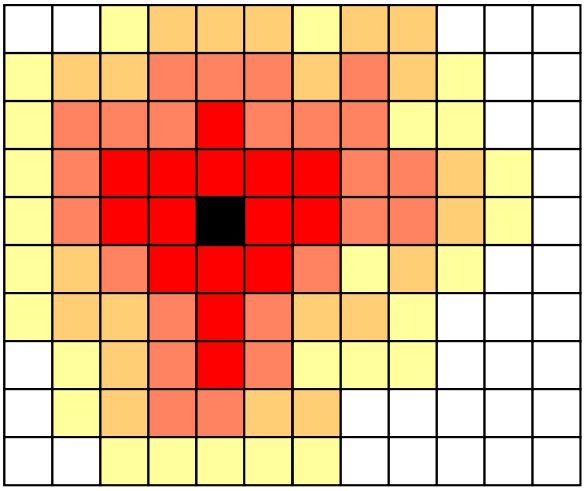


Figure 4: Path loss map in a 2D space segmented in cells (for a single transmitter cell)

The map is calculated with the model or input files we described before, we just take cell locations and cell IDs instead of specific node locations and node IDs. The parameters `SN.wirelessChannel.xCellSize`, `SN.wirelessChannel.yCellSize`, `SN.wirelessChannel.zCellSize` set the cell size (default = 5m). The smaller it is, the more fine-grained and accurate is your path loss map but also the more memory is needed to store it. Imagine you just have a 2-dimentional field 100m by 100m and you would like to have a cell of 1m y 1m, this results in 10,000 cells. This in turn results in $10{,}000^2$ = 100,000,000 path losses. With several bytes per path loss element (we store information besides the path loss) this can mean GBytes of memory. Our algorithm is smart and does not keep all possible combinations, but you get the idea on how fast can the state-space explode and also the processing time searching through these cells. Adding a 3rd dimension can aggravate matters, so be aware of the values you give to these parameters. In the wireless channel trace messages there is information about the size of the path loss map and the time it took to initialize it. This information can help you decide whether your choice of cell size with respect to the field is memory- and computation- efficient. Another parameter related to mobility in the wireless channel is `SN.wirelessChannel.onlyStaticNodes`. If we do not have any mobility in our scenario then we can declare this parameter true and save a lot of memory space and computation time. In this case, the space is not broken up into cells (the cell parameters do not matter) and the exact node locations are used in path loss computations much like Castalia 1.3 and below did.

Generally in Castalia, the modeling and computations are based on cells. When we do not have mobility, the nodes are treated as special cells where their location is acquired in a different manner, but all the rest of the code remains the same.

4.1.3 Temporal variation modeling

Another very important aspect of the wireless channel is the temporal variation. This is especially pronounced in rapidly changing environments as those experienced in a BAN. Figure 5 shows a typical profile of channel variation. Notice the sharp drops (measured up to -50dB in our BAN experiments) and that most of the time the channel is below the average path loss (0dB) (e.g., 2/3 of the time in Weibull fading channels). There are several theoretical models to describe temporal variation, taking their names from corresponding complex distributions (e.g., Rayleigh, Weibull, Nakagami, Gamma, lognormal). From our measurements around the human body we have seen that no single model describes temporal variation best. For that reason we tried to keep our modeling general but still expressively powerful to describe any temporal variation the measurements were showing.

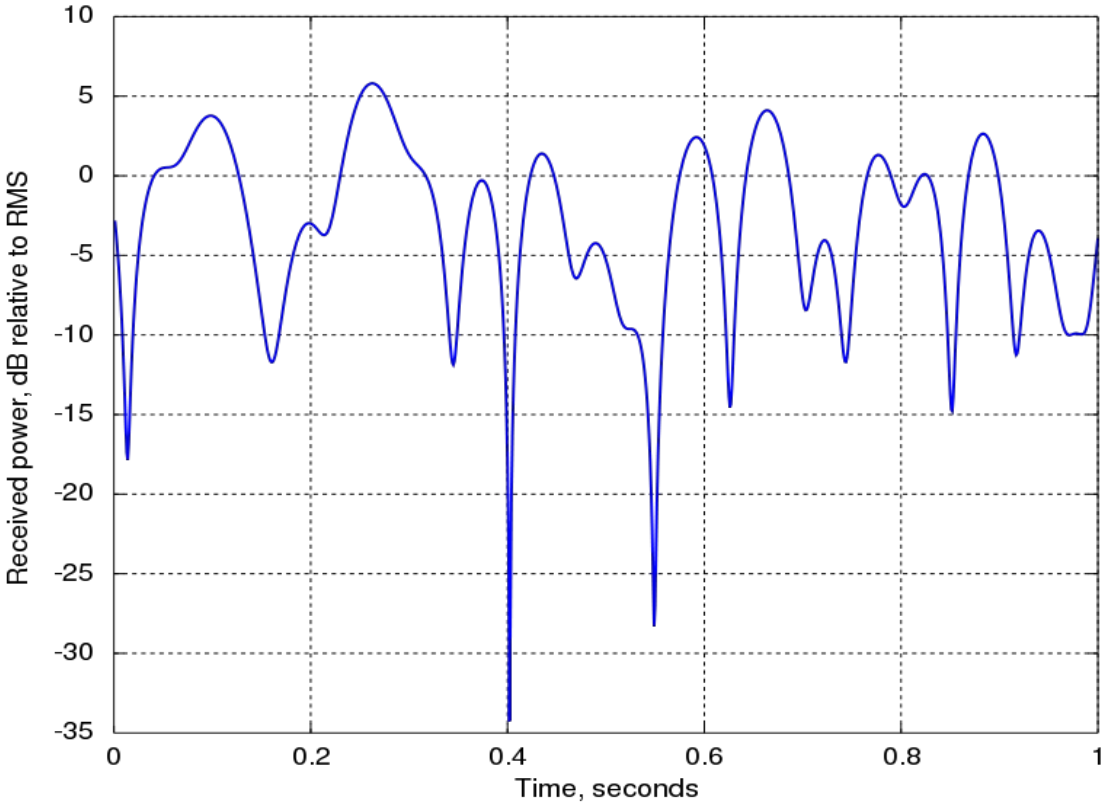


Figure 5: Typical temporal fading in wireless

In Castalia when we have to calculate the path loss at a specific moment, we first find the average path loss from the state we have stored during channel initialization (i.e., building the path loss map either using the model or the input files, as described in section 4.1.1) and then we have to find the component of the path loss due to temporal variation. To do this we

have kept the last “observed” value (in reality the last value we computed) and the time it has passed since then. These two numbers should define a probability density function (pdf) that we draw our new value from. Obviously, if little time has passed, then the bulk of the probability in this pdf should be in values close to the last observation. If the last observation is a deep fade (e.g. -40 dB) then the pdf should “boost” bigger values. The problem is that we cannot produce those pdfs dynamically from a model. They have to be produced from our experimental measurements. This in turn implies that we cannot have a pdf for any combination of last observation (dB value) and time passed. Instead we have to declare for what dB values and what times we are providing the pdfs. Then find a way to describe the pdfs in a manner that is accurate enough and computationally cheap. All this is done in a specially formatted file. The.ini file parameter is -as you have probably guessed- is the name of that file: `SN.wirelessChannel.temporalModelParametersFile`

The file is formatted in the following way: (strings min_value, step, max_value, t1, t2, tn, and T should be replaced with floating point numbers. The expression{pdf description} is explained shortly after.

```
Signal variability (dB):  min_value:step:max_value
Correlation times (msec): t1,t2,…tn
Coherence time (msec): T
T: {pdf description}
tn,min_value: {pdf description}
tn,min_value+step: {pdf description}
tn,min_value+2step: {pdf description}
…
tn,max_value: {pdf description}
tn-1,min_value: {pdf description}
…
tn-1,max_value: {pdf description}
…
t1,max_value: {pdf description}
```

So the file describes the values and times it will provide pdf descriptions for, and then gives these pdf descriptions. It also gives an extra time which we call “coherence time” (in lieu of a better name) and an extra pdf for it. This is a large time, beyond which, it does not matter what was the last observed value and we just draw our number from its corresponding pdf.

Now, what is the pdf description? It is a generic way to describe any pdf (in a quantized way) that also makes drawing a number from it computationally fast. In its simplest form is an array of dB values, say 100 values, space-separated. To draw a number, we pick a random number between 1 and 100, and then we draw the value with the same index. In that way we can arbitrarily describe any pdf (within some accuracy). For example, let's take a smaller array with just 10 values (thus when drawing a value we pick a random number between 1 and 10): `23 -23 -23 -23 -23 10 10 10 -5 15`. This describes a pdf where value -23 has probability 0.5, value 10 has probability 0.3, and 0.1 probability for values -5 and 15. Now you understand that we are loosing some accuracy because of the limited number of values we have (if we have 100 values we are limited to probabilities of 0.01). The tails of the distributions we are concerned with are important though, so we need to capture their values which correspond to really small probabilities. We could increase the number of values we have to 1000 or 10,000 and allow for many duplicate values, but this would be a waste of memory. There is a more elegant way to do it that incurs an almost insignificant increase in computation time. We can define levels of draws. So at the top level we may have 10 buckets (usually filled with values), which all represent 0.1 probability. One of these buckets instead of having a value it can have a letter, that points is to the next level. If we the random number we pick chooses the letter, then we have to draw again from another array of values/letters. So if the second level has 5 values then each of these values has 1/10 * 1/5 = 0.02 probability. An example looks like this:

```
23 -23 -23 -23 -23 10 10 10 -5 A; A= 15 15 15 3.5 3.5
```

This defines a pdf very similar to the example before but now value 15 has probability 0.06 and there is a new value 3.5 with probability 0.04.

This is the general expression for {pdf description} ([] means optional):

```
pdf:= level; [letter= level;] ... [letter= level]
level:=  number ... number [letter] ... [letter]
```

There is a limit to the depth of levels that we can define, but for most practical reasons there is no point in going beyond level 3 or 4. In the temporal parameters file we give with the `BANtest` scenario we have taken a range -31:1:11, times of 1000ms, 250ms, 10ms which results in 129 pdfs. Our pdfs have 2 levels with 101 buckets in the first level and 10 in the second. We also have coherence time = 5secs and a 2 level pdf with 1001 buckets in the first level and 10 in the second. The total file size is 118Kbytes.

4.1.4 Delivering signals to the Radio module

In Castalia versions earlier than 3.0, the wireless channel was responsible for calculating the interference a receiver “sees”, calculate the SINR (signal to interference plus noise ratio) and based on radio parameters decide whether a packet will be successfully received. If yes, then it would send the packet to the radio. So the wireless channel module was delivering packets to the radio of nodes. This modeling worked fine but it did not allow for multiple radio modes to co-exist in a network. Furthermore, it made fine-grain dynamic interference calculation challenging. Since Castalia 3.0 and the complete restructuring of the radio model, we were able to revisit the operation of the wireless channel too. Now the wireless channel just sends the signal to the radio and lets the radio calculate its interference, its (dynamically changing) SINR and decide whether or not it receives a packet. So now the wireless channel just needs to send messages to the radio that carry information about the signal, such as: modulation, bandwidth, carrier frequency, and most importantly, the strength of the signal in dBm. Based on the path loss (average path loss + temporal variation) and the transmission power of a transmitter, the wireless channel can calculate the signal strength received at a node.

Which signals do we send to a radio module? All of them, irrespective of how weak they are? That would be a waste of resources; both computation time and memory. A signal transmission would result to a signal reception in all existing nodes irrespective of how far they are from the sender. Moreover if we have mobility, one cell would affect all other cells, resulting in the biggest possible path loss maps. Instead we can be smarter and set a signal strength threshold that beneath it does not make sense to deliver a signal. What would this threshold depend on? Obviously, the radio sensitivity. Should it just be the radio sensitivity? No, because a signal can be weaker than the radio sensitivity but it can still cause interference to another signal. Imagine two signals being heard at a receiver, one is at the sensitivity threshold, the other is 1dB smaller. If we did not deliver the smaller signal, the first one would be processed and the packet that it carried would be received with no problems. If we deliver both signals, a collision would probably occur. So how much lower than the radio sensitivity should we go? 10dB is usually more than enough and 5dB should be the minimum. Because there are tradeoffs at play we decided to make the signal delivery threshold a parameter of the wireless channel.

```
double signalDeliveryThreshold = default (-100);
```

-100dBm is a good value for both the BAN radio and the CC2420 we have defined. If you are using CC1000 then you should probably choose -103 or lower.

4.1.5 Choosing naive models

It would be useful to define simpler models (up to the rather simplistic disk model) so that simulation results can be compared with results from other simulators and more importantly so that the user can test different hypotheses on why a distributed algorithm does not work (or underperforms) when more realistic assumptions are taken into account. This is especially true with models of communication, especially the lower-level ones (channel and radio).

In an omnetpp.ini file, we can make the wireless channel simpler by simply setting:

```
SN.wirelessChannel.sigma = 0
SN.wirelessChannel.bidirectionalSigma = 0
```

This way all nodes at a certain distance from a transmitter get the exact same signal strength and all links are perfectly bidirectional (i.e., the quality of A→B is the same as the quality of B→A).

If we can also provide sharp thresholds for the radio reception (i.e., perfect reception of a packet or no reception at all) then we end up with the simple unit disk model. Indeed, for all the radios we have defined, we provide a special mode with an ideal modulation scheme. To choose it, simply set:

```
SN.node[*].Communication.Radio.mode = "IDEAL"
```

So by setting the two sigmas of the wireless channel to 0 and the radio mode to "IDEAL" a user can emulate the naïve -but still prevalent- unit disk communication mode (i.e., transmissions within a certain range from a transmitter are perfectly received, and outside this range not received at all).

When adopting a unit disk model, a user can control the range of the disk by controlling the SN`.wirelessChannel.PLd0` parameter. Assume you need the range of the disk to be 50m then you should set PLd0 = (TxPowerUsed_dBm – max(receiverSensitivity, noisefloor+5dBm)) – 10*pathLossExponent*log(50) [12]

The user can further play with the `collisionModel` parameter of the Radio module to get simpler models. We will explain this in the section 4.2.3.

12 In the radios we have defined so far, SN.node[*].Communication.Radio.receiverSensitivity is greater or equal to (SN.node[*].Communication.Radio.noiseFloor +5dBm)

4.2 The Radio

The radio module tries to capture many features of a real low-power radio, one that is likely to be used in wireless sensor network platforms. The main features of our Radio module are:

- Multiple **states**: transmit, receive/listen, multiple (configurable) sleep states
- Transition **delays** from one state to another.
- Multiple (configurable) **transmission power levels**
- Different **power consumption** for the different states and Tx levels used.
- Multiple **modes of operation** (defined by modulation, datarate, bandwidth, noise floor, and other parameters) that can dynamically change.
- Multiple **modulation** schemes natively supported (FSK, PSK, DiffQPSK, DiffBPSK, Ideal modulation with 5dB threshold).
- Ability to define **custom modulation** schemes by defining SNR→ BER mapping
- Continuous calculation of **RSSI** (Received Signal Strength Indicator)
- **CCA** (Channel Clear Assessment) capability; interrupts to the MAC module.
- Fine-grain **interference** calculation (dynamically changing during packet reception) and calculation of exact **bit errors** in a packet

4.2.1 The Radio Parameters file

To define the main operating parameters of a radio we are using a file which follows a specific format. We have already defined 3 radios that you can find in `Simulations/Parameters/Radio/`. These are: `BANRadio.txt CC1000.txt CC2420.txt`. BANRadio describes the narrowband radio proposed in the IEEE 802.15 Task Group 6 documents. CC2420 and CC1000 define the real radios of the same name by Texas Instruments. The parameter `RadioParametersFile` of the Radio module points to this file. The module will read it and parse it. Here is the format of a Castalia Radio Parameters file:

Any line beginning with '#' is considered a comment.

The files should contain 5 sections each starting with the line

RX MODES

TX LEVELS

DELAY TRANSITION MATRIX

POWER TRANSITION MATRIX

SLEEP LEVELS

The sections can appear in any order. In the radios we have defined, we follow the order shown above. Section RX MODES contains one or more lines of the following format:

Name, dataRate(kbps), modulationType, bitsPerSymbol, bandwidth(MHz), noiseBandwidth(MHz), noiseFloor(dBm), sensitivity(dBm), powerConsumed(mW)

All quantities are numbers except from Name, which is an arbitrary string and modulationType which can take only the following values: FSK, PSK, DIFFBPSK, DIFFQPSK, IDEAL, CUSTOM. Here's an example from CC2420.txt:

```
normal, 250, PSK, 4, 20, 194, -100, -95, 62
```

Section TX_LEVELS should have two lines. The first line starts with the string "Tx_dBm" followed by n numbers (space-separated). The second line starts with the string "Tx_mW" also followed by n numbers separated by at least one space. As you can understand, the first line lists the output power of the different transmission levels in dBm and the second line how much energy the radio is spending when transmitting in a power level. The order of the power levels should be kept the same in both lines. In the radio files we have already defined, we chose to go from larger to smaller. Here's an example from CC2420.txt defining the 8 possible transmission power levels:

```
Tx_dBm 0 -1 -3 -5 -7 -10 -15 -25
Tx_mW 57.42 55.18 50.69 46.2 42.24 36.3 32.67 29.04
```

Section DELAY TRANSITION MATRIX specifies delays (in msec) to switch between the three main radio states: RX (receive), TX (transmit) and SLEEP. This section should contain a line corresponding to (and starting with the name of) each state. Following the name of a state there are three numbers defining transition times in milliseconds from RX, TX and SLEEP states respectively to the current state given first in each line. Below is an example from CC2420.txt:

```
RX     -     0.01  0.194
TX     0.01  -     0.194
SLEEP  0.05  0.05  -
```

In this case, it takes the radio 194μsec to change from SLEEP state to either RX or TX, 10μsec to change between TX and RX states and 50μsec to enter the SLEEP state. Note that each line contains '-' instead of a number in the cells corresponding to no transitions.

Similarly to the previous section, POWER TRANSITION MATRIX section follows the same format to specify the consumed power (in mW) during the time when state transitions are taking place. In CC2420.txt configuration it can be seen that transitions to SLEEP state consume 1.4mW while any other transitions take 62mW:

```
RX     -     62    62
TX     62    -     62
SLEEP  1.4   1.4   -
```

Lastly, section SLEEP LEVELS defines different sleeping modes (or levels) available to the radio. Sleep levels exhibit different power consumption. The sleep levels are ordered from the most “shallow” sleep (i.e., the one with the more power consumption) to the deepest sleep. While in a sleep level, the radio can only go to the sleep level immediately up or down. You have to be in the top (shallowest) level to enter the RX or TX state. When going from RX or TX to sleep, you first go into the shallowest level and gradually go to a deeper sleep level if desired. These transitions are handled automatically by the radio module. The user just defines the desired sleep level when the radio is put to sleep and the appropriate transitions, delays, and power consumption are taken into account. The SLEEP LEVELS section should contain at least one line of the following format:

Name, power(mW), delay up(ms), power up(mW), delay down(ms), power down(ms)

Name is any string to denote the name of the level and power is the power consumption at that level. Delay up and delay down denote time taken to move to the level above and below (which respectively are defined by lines above and below), while values of power up and down correspond to the energy consumption value during the transition process. In CC2420.txt only a single sleep level is defined as follows (note that no transition values are given, since there are no other sleep levels):

```
idle 1.4, -, -, -, -
```

4.2.2 Radio Module Parameters

Apart from the Radio Parameters file, the radio module defines a set of parameters that can be specified from within configuration files (.ini files). The list of these parameters can be found in the Radio.ned file and is presented below:

```
string RadioParametersFile = default ("");
```

This is a path to the radio parameters file as explained in the previous section. The path can be absolute, or relative to the directory which contains the simulation configuration (.ini) file.

```
string mode = default ("");
```

This parameter allows us to select the starting RX mode from the list defined in the radio parameters file. Default value (empty string) means that the first mode listed will be used. Modes can be changed dynamically during the simulation as will be explained in section 4.2.4.

```
string state = default ("RX")
```

This parameter specifies the starting state of the radio once simulation begins. By default the radio will start in the listening (receiving) state.

```
string TxOutputPower = default ("");
```

This parameter defines the starting transmission output power level to be used, e.g. -5dBm. Note that only power levels that were declared in the radio parameter file can be used. Default value (empty string) will cause the highest (first) output power level to be used.

```
string sleepLevel = default ("");
```

This parameter allows selecting the default sleep level (sleep depth) that will be used by the radio when a transition to SLEEP state is requested. The default value (empty string) means that the first level defined will be used. This corresponds to the fastest and most energy consuming sleep state.

```
double carrierFreq = default (2400.0);
```

This parameter allows selecting the starting carrier sense frequency of the radio (in MHz).

```
int collisionModel = default (2);
```

This parameter defines the collision model used by the radio to compute the impact of various incoming signals on each other's reception (this process is called interference). More information on this parameter and various available collision models will be provided in section 4.2.3

```
double CCAthreshold = default (-95.0);
```

This parameter defines the value of Clear Channel Assessment (CCA) threshold used by the radio when determining whether the wireless channel medium is clear. In particular, if the RSSI reading (i.e., an estimation of the cumulative power of incoming radio signals) exceeds this threshold, then the radio will report channel as busy (i.e. not clear).

```
int symbolsForRSSI = default (8);
```

This parameter specifies the amount of symbols required by the radio to perform RSSI calculation.

```
bool carrierSenseInterruptEnabled = default (false);
```

This parameter allows us to turn on an interrupt capability of the radio module which will inform upper layers (in particular MAC layer) when the channel state moves from clear to busy (i.e. when CCAthreshold is passed). This capability is present in some real radios, however it is turned off by default to ensure that carrier sense interrupt only appears when it is intended to be used.

4.2.3 Reception and Interference calculation

The Radio module operates on signals that are provided from the wireless channel module. Section 4.1.4 explained how signals are delivered. Signals last for some time since they are encoding a packet's transmission (OMNeT messages called `WC_SIGNAL_START` and `WC_SIGNAL_END` denote the duration of a signal/packet). Thus, at any time, the radio module has a list of incoming signals that are affecting each other's reception. If a signal is received without any other signals being received at the same time, then its reception is decided thus: Based on the noise floor (a parameter of the RX mode of radio operation) and the received signal strength, we calculate the SNR. Based on the SNR, the modulation scheme, the data rate, (again, parameters of the RX mode of radio operation) and length of the packet/signal we calculate how many bit errors has the packet/signal experienced. Based on the encoding and bit errors, we know if the packet was received correctly. When we add into the mix interfering signals then we need to calculate the Signal to Interference Ratio (SINR or SIR) and do the above calculations at *every signal change*. Bit errors are calculated up to the point of the last signal change. If a signal changes then we calculate SINR and bit errors for the last unchanged portion of the packet/signal.

How is interference calculated based on the reception of other signals? We simply add up the signal strengths of the interfering signals[13]. We also add up the power of the thermal noise (i.e. the noise floor) and we have the SINR.

The user has the option to opt for simpler interference/collision models by setting the parameter `SN.node[*].Communication.radio.collisionModel`. If set to 0 *there are no collisions happening*. If set to 1 there is a simplistic model for collisions. In this case, if two nodes are concurrently transmitting and the receiver can receive both of their signals -even minimally- then there is *always* a collision at the receiver. Notice that for the same case, with additive interference model, we can have two possibilities: a) have a collision or b) the receiver receives the stronger of the two transmissions (if it is strong enough). It will all depend on the specific SIR at the receiver node. Setting the collision model variable to 2 uses the additive interference model where transmissions from other nodes are calculated as

13 Recent research has shown that the total interference is somewhat less that the simple addition of the interfering signals. In practice, you should not see any difference in the simulation unless you have a high-interference scenario, where one node is interfered with by 4 or more other nodes each time.

interference by linearly adding their effect at the receiver. In chapter 3 you have already seen the effect of using different collision models in the radioTest simulation scenarios.

4.2.4 Dynamically adjusting radio parameters

Section 4.2.2 illustrated a list of radio module parameters that allow to specify starting values of radio state, reception mode, sleep level, transmission power output, CCA threshold and carrier frequency. Values of these parameters can be set in the omnetpp.ini, but what if we would like to dynamically change the values for some of these parameters within a specific simulation run? After all, in real platforms, many or the radio parameters are controllable by the processor. For this purpose we have defined and implemented a function (overloaded 4 times with 4 different argument sets) called `createRadioCommand` to assist with issuing commands to the radio.

First it is important to point out that most communication between Castalia modules is handled using OMNeT messages. Consecutively, issuing a command to the radio module involves two steps: 1) create the correct control message (command) and 2) send it to the right module. Step one is largely automated using one of the `createRadioCommand` functions which returns a command ready to be sent. Here are the different forms you can use the function (they are defined in `RadioSupportFunctions.h`):

```
RadioControlCommand
      *createRadioCommand(RadioControlCommand_type,double)
RadioControlCommand
      *createRadioCommand(RadioControlCommand_type,const char *)
RadioControlCommand
      *createRadioCommand(RadioControlCommand_type,BasicState_type)
RadioControlCommand *createRadioCommand(RadioControlCommand_type)
```

It can be seen that all 4 functions return an object of `RadioControlCommand` type that can be transferred between OMNeT modules. Additionally, each function requires a `RadioControlCommand_type` argument. This type is defined in the file `RadioControlMessage.msg` and can take the following values:

```
SET_STATE
SET_MODE
SET_TX_OUTPUT
SET_SLEEP_LEVEL
SET_CARRIER_FREQ
SET_CCA_THRESHOLD
SET_CS_INTERRUPT_ON
```

```
SET_CS_INTERRUPT_OFF
```

Each of the four functions above is only compatible with a subset of the available command types, depending on the argument that needs to be provided. More specifically, a double argument is required for SET_TX_OUTPUT, SET_CARRIER_FREQ and SET_CCA_THRESHOLD commands. A string (char *) argument is needed for SET_MODE and SET_SLEEP_LEVEL commands, while a BasicState_type value (corresponding to one of the 3 radio states – RX, TX and SLEEP) can only be used with SET_STATE command. Finally, no argument is required for SET_CS_INTERRUPT_ON and SET_CS_INTERRUPT_OFF radio control commands.

The second step to control the radio is passing the created command to the radio module. Usually, only two modules that require interaction with the radio: the MAC and the Application. In the Castalia architecture, the MAC module is connected to the radio module since they are directly exchanging packets and messages. Consecutively, the MAC module interface defined in VirtualMac.h file provides a helpful function `toRadioLayer()` that allows to send a message (or packet) to the radio. Below are some examples of controlling the radio from within MAC module's code:

```
toRadioLayer(createRadioCommand(SET_STATE,SLEEP));
toRadioLayer(createRadioCommand(SET_TX_OUTPUT,-5));
toRadioLayer(createRadioCommand(SET_CS_INTERRUPT_ON));
```

Application module on the other hand is only directly connected to Routing (Network) module, preventing it from sending messages to radio module directly. However, Castalia's communication stack has been designed in such a way as to automatically pass messages up and down the stack depending on their kind. In other words, Routing module will be able to accept a command designated to the radio module, but instead of trying to process it, the command will be forwarded down the communication stack to the next layer below (MAC). Similarly, MAC module will forward the command further and deliver it to the radio module as required. The application module interface defined in VirtualApplication.h provides a `toNetworkLayer()`function that can be used to send radio control commands from within the application's code:

```
toNetworkLayer(createRadioCommand(SET_STATE,SLEEP));
toNetworkLayer(createRadioCommand(SET_TX_OUTPUT,-5));
toNetworkLayer(createRadioCommand(SET_CS_INTERRUPT_ON));
```

When controlling the radio from the layers above, make sure there is proper cooperation between the layers (e.g. avoid both layers truing to control the same radio aspect).

4.3 MAC

The Medium Access Control protocol is an important part of the node's behaviour, thus there is a separate module that defines it. In Castalia we have four main MAC modules implemented: 1) TunableMAC, a duty-cycled MAC which exposes many parameters to the user and the application for tuning. From TunableMAC we also get the behaviour of a simple CSMA/CA MAC protocol. 2) the popular TMAC. From TMAC we can also get S-MAC by just setting couple of parameters (T-MAC is an enhancement of S-MAC allowing extendible active times). 3) IEEE 802.15.4 MAC. This is the standard for low power wireless networks, although *not* prevalent in WSN. 4) IEEE 802.15.6 MAC draft proposal for Body Area Networks (BAN).

4.3.1 Tunable MAC

Our initial motivation in building Castalia was to test a highly tunable MAC protocol in realistic channel radio conditions. We provide this highly tunable protocol with the standard distribution of Castalia because it can approximate several duty-cycling protocols out there (e.g., B-MAC, LPL). However it should be noted that this protocol was built with broadcast communication in mind (i.e., no unicast) thus it does not support acknowledgments, RTS and CTS control packets. TunableMAC employs a CSMA mechanism for transmissions, so it is a contention-based MAC. It can be tuned in regards to its persistence and backing off policies. Another major function is to duty cycle the radio and to transmit an appropriate train of beacons before each data transmission to wake up potential receivers (since the nodes are not aligned in their sleeping schedules). It also provides several other parameterized functions such as retransmissions, probabilistic transmission, and randomized TX offsets. Look in the file

`src/node/communication/mac/tunableMac/TunableMAC.ned`

for a complete set of the module's parameters. Note that the default values for this module implement a non-persistent CSMA-CA protocol with *no* radio duty cycling. Let us see the 12 most important parameters that can be tuned:

```
double dutyCycle = default (1.0);
```

This is the fraction of time that the node stays on listening to the channel. For s = (1 - dutyCycle) fraction of the time the node sleeps. This is probably the most important parameter affecting energy consumption as it can drastically reduce listen time.

```
int listenInterval = default (10);
```

This is the time (in msecs) the node stays on listening each cycle. Knowing the duty cycle we can then define the time the node sleeps each cycle. After we had one listen and one sleeping interval, the cycle starts again. We would like the listen interval to be small so the sleeping interval for a given duty cycle is small too thus latency in data delivery is minimized. However, if we make the listen interval too small, packets won't be able to be received in full (either beacon or data packets). A good time for a listening interval is between 5ms and 10ms for the radio of 250Kbps we usually use. You should play around to find a good value for your scenarios.

```
double beaconIntervalFraction = default (1.0);
```

When we have a duty cycle and nodes that are not synchronised, we need a way to get the attention of a sleeping node before we transmit our data. A standard method is to use a train of beacons before our transmitted data. If we need to guarantee that all the possible receiving nodes will wake up, we should make the train of beacons at least as long as the sleeping interval. But imagine you have many neighbours and you do not need all of them to wake up. Assume that you want (statistically) half of them to wake up. Then you should make the beacon interval half of the sleeping interval. This parameter expresses the *fraction* of the maximum beacon interval (= sleeping interval) that beacons are transmitted. The smaller this is the less energy we spend, but the less chance we have to wake up a neighbour.

```
double probTx = default (1.0);
```

Probability of Transmissions. When a piece of data needs to be transmitted (or retransmitted) we perform the action with a certain probability; often assumed by many protocols to be 1. This value combined with the number of retransmissions can create any *expected number of transmissions per node*, even non integer values. For example if we have 6 retransmissions (so 7 transmissions in total) and probability of transmission 0.5, then we end up with 3.5 expected transmissions per node per data value we want to transmit.

```
int numTx = default (1);
```

Number of transmissions. For each piece of data needed to be transmitted how many times do we try to transmit it. Obviously the larger this parameter is the more energy is spent but more performance (reached nodes) can be achieved.

```
int randomTxOffset = default (0.0);
```

Random Transmission Offset. Before attempting to transmit (which starts with sensing the channel to check whether it is free) we wait a random time uniformly distributed in [0..Random Transmission Offset]. This randomness can significantly help to avoid collisions that could be very common in a broadcast type scenario. If a node transmits its data and four of its neighbors receive it and decide to retransmitted immediately then it is very probable to have collisions (even if we are sensing the channel). Adding the randomness in transmission time we can avoid such collisions. Note that the default value is 0 (meaning no randomness) since standard CSMA-CA does not employ this technique.

```
int reTxInterval = default (0.0);
```

Retransmission Interval. The interval between retransmissions. With this parameter we can effectively spread out our expected transmissions.

```
int backoffType = default (1);
```

This parameter relates to carrier sensing. As we mentioned earlier, a CSMA technique is employed normally by the MAC. If the default non-persistent CSMA is chosen then whenever the MAC backs off every time the channel is not clear for transmission.. The backoff type parameter specifies how is this backing off interval determined. If set to 0, then we set the backoff timer to the duration of a sleeping interval. If set to 1, we back-off for a constant time: *backoffBaseValue*. If set to 2, then the backoff timer depends on the consecutive *times* we found the channel not to be clear. This is the relation backoff timer = *(backoffBaseValue)* · *(times)*. If we set the parameter to 3 then again it depends on the consecutive *times* we found the channel not to be clear: backoff timer = $(backoffBaseValue)^{times}$.

```
int backoffBaseValue = default (16);
```

This is the parameter we used above in expressing how long we are backing off for each different backing off type.

```
double CSMApersistance = default (0);
```

This parameter determines the persistence of CSMA. The default value (0) means a non-persistent CSMA, i.e., after sensing the channel is not free, the node backs-off for a certain random amount of time (determined by the backoff scheme and the backoff base value) before trying to sense the channel again. In 1-persistent CSMA (CSMApersistance = 1) the node does not back off. It keeps on checking the channel until it finds it free and then it

transmits. Ideally the node is notified immediately when the channel is free. In reality radios do not offer this notification function, so the node (i.e. the microcontroller running the MAC) has to poll the radio to find out the state of the channel. In Tunable MAC we poll the radio every 0.128msecs. p-persistent CSMA (0<p<1) works like 1-persistent CSMA in the sense that it keeps polling the channel until found free, but when it is found free it transmits only with probability p.

```
bool txAllPacketsInFreeChannel = default (true);
```

A parameter to control the behaviour of the node when the channel is found free. The default value allows all packets in the buffer to be transmitted without the need to sense the channel again (or transmit separate beacons in the case of duty cycle). If it is set “false” then only one packet from the MAC buffer will be sent, and any other packet already in the buffer will have to undergo the carrier sensing procedure (and the possibly sending beacons procedure) again. Generally it is better to transmit all packets in the buffer when the channel is found clear. Only consideration is fairness, and it some extreme traffic cases a node can hog the channel starving the other nodes.

```
bool sleepDuringBackoff = default (false);
```

If there is a duty cycle in place then whenever we backoff we also go to sleep. This is set behaviour. However, if we have no duty cycle then there is no set way to behave. We can go to sleep, (since we are just waiting) but then, when it is time to wake up there is an extra delay before we can sense the channel. This extra delay slightly increases the opportunity for collisions, but on the other hand a node can save considerable energy (especially in heavy traffic where it is backing off often). Since simple CSMA-CA does not care about energy efficiency the default value for this parameter is “false”

The rest of the parameters define generic aspects of a MAC (e.g., how many bytes a data frame and a beacon are, what is the byte overhead, or the size of the MAC buffer) and also capture important information from the radio (data rate, radio overhead, time for the RSSI register to become valid). It is important that these radio-related parameters are explicitly exposed to the MAC (instead of automatically read by the radio module) so that the user (and the designer) can be fully aware of what influences the MAC.

4.3.1.1 Dynamically adjusting Tunable MAC parameters from the application module

As with the radio case, we would like to change many of the MAC parameters through the application code. We can send special messages/commands to TunableMAC to control it. This time we have not defined helper functions to create the commands so we have to be somewhat more verbose in the code we write at the application module. The different commands accepted by Tunable MAC are defined in:

`src/node/communication/mac/tunableMac/TunableMacControl.msg`

This implies we have to add this line in the module code that wants to control TunableMAC:

```
#include “TunableMacControl_m.h”
```

Then to create a control command we do:

```
TunableMacControlCommand *cmd = new TunableMacControlCommand
                ("TunableMAC control command", MAC_CONTROL_COMMAND);
cmd->setTunableMacCommandKind (kind);
cmd->setParameter(value);
```

`kind` is an enum that can take the following values:

SET_DUTY_CYCLE

SET_LISTEN_INTERVAL

SET_BEACON_INTERVAL_FRACTION

SET_PROB_TX

SET_NUM_TX

SET_RANDOM_TX_OFFSET

SET_RETX_INTERVAL

SET_BACKOFF_TYPE

SET_BACKOFF_BASE_VALUE

`value` is a variable of double type.

After we create the command we send it in similar way we send radio commands. From an application module we call:

```
toNetworkLayer(cmd);
```

4.3.2 T-MAC and S-MAC

T-MAC is a popular MAC for WSN as it employs many techniques to keep the energy consumption low (using aggressive duty cycling and synchronization) while trying to keep performance (e.g. packet delivery) high by adapting its duty cycle according to the traffic needs. S-MAC can be seen as the predecessor of T-MAC as it initiated many of the techniques but uses a more rigid duty cycle. One Castalia module (TMAC) offers the functionality of both protocols. The implementation of T-MAC in Castalia was a complicated and time-consuming task since many of the protocol's practical details were not explicitly stated in the original paper. For example, details about time-synchronisation were absent. Time-synchronization was dealt only by referring to S-MAC. More importantly, the S-MAC sync technique was not suitable for the new ideas TMAC was introducing, so decisions had to be taken to keep the performance of TMAC high. On top of this we added extra functionality that is not explicitly described in the original paper such as a fixed number of retransmissions for failed unicast packets. The details of our implementation of TMAC, focusing on protocol ambiguities and decisions made, are described in our WCNC 2010 paper [6]. The parameters that the TMAC module takes can be found in:

`src/node/communication/mac/tMac/TMAC.ned`

We start again with some parameters to control collecting traces and debug output. We then define the sizes of the different control packets in TMAC (SYNC, ACK, RTS, CTS) as well as the maximum frame size for data and its overhead. Also the buffer size of the MAC is given. Then 12 parameters follow that define the behaviour of the protocol. Let's see them in more detail. If you want to stay as close to the original TMAC leave these parameters to their default values.

```
int maxTxRetries = default (2);
```

This number of transmission attempts of a single unicast packet that TMAC will perform. A transmission is considered successful only if acknowledgment packet is received from the destination node. Sending an RTS packet is also considered as a transmission attempt. Note that this parameter does not apply to broadcast packets.

```
double frameTime = default (610);
```

The length of each frame period for all nodes (in milliseconds). Nodes try to synchronise the start and end of each frame with a global schedule (with the possibility of more than one schedules). Note that this refers to the duration of the whole frame; the active and inactive portions of each frame are determined dynamically and individually for each node.

```
double contentionPeriod = default (10);
```

The duration of contention interval (i.e. interval where transmissions of randomized), in milliseconds, for any transmission attempt. The major effect of this parameter is to avoid transmission interference from neighbouring nodes.

```
double listenTimeout = default (15);
```

The duration of listen timeout in milliseconds (can also be called activation timeout). This parameter defines the amount of time which has to pass without any activity on the wireless channel in order for a node to go to sleep in the current frame.

```
double waitTimeout = default (5);
```

The duration of timeout for expecting a reply from another node (in milliseconds). This reply may be a CTS packet or an ACK packet. If no reply is received after this time interval, then transmission attempt is considered failed and transmission attempt counter is decremented.

```
double resyncTime = default (6);
```

The interval between broadcasting synchronization packets (in seconds). The value of this parameter is directly related to the clock drift of nodes in the simulation network. Our experiments showed that 40 seconds is an adequate value to use with current clock drift model of Castalia.

```
bool allowSinkSync = default (true);
```

If this value is set to 1 (true), TMAC will attempt to extract information from higher layers (i.e., application module parameter `isSink`) in order to find out whether the current node is marked as 'sink'.

This parameter allows 'sink' nodes to avoid contention interval when creating a synchronisation schedule for the network, thus allowing for faster synchronisation, and consequently, better throughput (especially if packets need to be sent early in the simulation)

```
bool useFrts = default (false);
```

This parameter refers to the use of future request to send (FRTS) as defined by the creators of TMAC algorithm. In our current TMAC implementation we do not provide support for this

parameter as we consider it to be addressing a specific issue, while not being part of the core TMAC algorithm

```
bool useRtsCts = default (true);
```

This parameter is an additional feature, which was not originally proposed in TMAC. It allows to turn off RTS and CTS packets, thus limiting any transmission to a simple DATA - ACK exchange between nodes. We find this parameter useful for situations where only small packets are being sent, thus making it unnecessary to actually reserve the channel for transmission (since reservation will take more time than transmission itself).

```
bool disableTAextension = default (false);
```

Another extra parameter that allows us to turn off the activation timeout extension. Since the flexible active period is the trademark enhancement of TMAC over SMAC, by disabling it and defining appropriate listen interval (10% of the whole frame) we are essentially implementing SMAC. Indeed we provide an ini file to include in your simulations that defines the appropriate parameters of the TMAC module to emulate the SMAC protocol.

```
bool conservativeTA = default (true);
```

Use conservative activation timeout, will ensure that MAC stays awake for at least 15 ms after any activity on the radio. For more info read [6].

```
int collisionResolution = default (0);
```

Choose a collision resolution mechanism from those, described in [6]. Possible values are:
0 - Retry contention immediately after losing the channel,
1 - Retry only when heard a CTS or RTS
2 - Retry only in the next frame

Finally 3 parameters relating to physical layer operations, such as data rate, delay to carrier sense and phy overhead are defined. Again as with TunableMAC is it important to expose the MAC user to these to show the dependence on the radio.

If you want to use SMAC then the following file defines TMAC parameters in such a way as to emulate SMAC (you can simply include it in your .ini file):
`Simulations/Parameters/MAC/SMAC.ini`

4.3.3 IEEE 802.15.4 MAC

The IEEE standard for wireless low-power short-range communications (802.15.4) defines, apart from the physical layer, the functionality of a MAC. We have implemented core functionality of this MAC in Castalia and we offer it starting with Castalia version 2.2. Castalia 2.3 included the important GTS functionality (a form of TDMA). We concentrated our implementation efforts in functions of the MAC that would help with Body Area Networks and left others unimplemented due to limited resources.

More specifically we implemented:

- CSMA-CA functionality (slotted and unslotted)
- Beacon-enabled PANs with association (auto associate)
- Direct data transfer mode
- Guaranteed time slots (GTS).

Features that are NOT implemented:

- Non-beacon PANs
- Indirect data transfer mode
- Multihop PAN topologies

We suggest you read the standard [7] to have a better understanding of what the protocol does. The brief description of its parameters here might not be adequate for full understanding if you have not studied the protocol before. The 802.15.4 MAC module has the usual communication module parameters (defining packet sizes and overhead) plus 17 protocol-specific parameters.

Let's start with the parameters that help set the different timing periods in the protocol. First, we have two parameters that (partly) define the active portion of a superframe (when the radio is on listening or transmitting), and the inactive portion. These are:

```
int frameOrder = default (4);
```

Specifies how long is the active portion of a superframe (also called "frame"), when radios are listening or transmitting. Active frame part = *aBaseSuperframeDuration* $\cdot 2^{\text{frameOrder}}$.

```
int beaconOrder = default (6);
```

Specifies how long is the full frame (active and inactive). This is the period between two beacons. Full frame = *aBaseSuperframeDuration* $\cdot 2^{\text{beaconOrder}}$.

So with the default values the active part of the frame is 16 times a variable called *aBaseSuperframeDuration*, while the full frame is 64 times that variable. What is *aBaseSuperframeDuration* though? It is equal to baseSlotDuration × numSuperframeSlots × symbolTime. Let's look at each of the three variables in the formula: symbolTime is derived by the radio parameters dataRate and bitsPerSymbol. For 802.15.4 radios the symbol time is 16μsec (250Kbps data rate with 4 bits per symbol). The other two variables are parameters of the aforementioned 17 parameters of the MAC.

```
int baseSlotDuration = default (60);
```

Denotes how many symbol times is the base slot variable.

```
int numSuperframeSlots = default (16);
```

Denotes how many slots are in the active portion of a superframe.

So using the default values we can calculate *aBaseSuperframeDuration* = 15.36msec. Which further means that using the default values for frameOrder and beaconOrder, we can calculate that the default value for the active portion of the frame is 245.76ms while the full frame is 983.04ms. The active portion of a frame is divided into slots that are used either for CSMA traffic, or for TDMA traffic (called GTS slots in the standard). As seen by the parameter above, we have 16 slots by default, so each slot is 245.76ms/16 = 15.36ms in duration.

Here are the rest of the 802.15.4MAC-specific parameters:

```
bool enableSlottedCSMA = default (true);
```

Enables the slotted version of the CSMA algorithm, explained in the standard.

```
bool enableCAP = default (true);
```

Allows a node to transmit DATA packets in the CAP period of a frame. Control packets are transmitted only in CAP regardless of this parameter's value

```
bool isFFD = default (false);
```

Is the node a full function device? These are the only devices which can act as coordinators.

```
bool isPANCoordinator = default (false);
```

Is the node the PAN coordinator?

```
bool batteryLifeExtention = default (false);
```

If set to true, it tries to reduce the randomisation offset in the slotted version of CSMA-CA algorithm.

```
int unitBackoffPeriod = default (20);
```

Specifies how long is the unit of time used in backing off. More specifically the standard uses a exponential backoff technique and the backoff time is: random(1…$2^{backoff\_exponent}$-1) × (unitBackoffPeriod × symbolTime). Backoff_exponent is a variable automatically updated by the protocol.

```
int macMinBE = default (5);
```

In calculating the backoff time, this is the minimum value that the backoff exponent can take.

```
int macMaxBE = default (7);
```

In calculating the backoff time, this is the maximum value that the backoff exponent can take.

```
int macMaxCSMABackoffs = default (4);
```

Maximum number of backoffs until the transmission of the packet is aborted and go for another retry (if there are any left).

```
int macMaxFrameRetries = default (2);
```

Maximum number of retries until the packet is considered lost and the upper layer notified.

```
int maxLostBeacons = default (4);
```

Maximum number of beacons lost until the node considers itself disassociated from the PAN coordinator.

```
int minCAPLength = default (440);
```

The minimum length of CAP period when GTS is used, defined in symbols

```
int requestGTS = default (0);
```

Allows a node to request a specified number of GTS slots from the coordinator. If the request is successful, DATA packets will be transmitted in the GTS slots assigned by the coordinator These slots are assigned dynamically according to availability. If no slots are available, the request will fail. Note that this is an easy way for a node to statically request a certain number of slots. A more dynamic solution would be for the application module to instruct the MAC module how many slots should it request. The current (parameter-based) solution is a shortcut when we have constant application traffic and we can figure out a priory an optimal way to share the slots among the nodes.

Then we have 6 parameters relating to the physical layer. These define delays going from one state of the radio to another, the data rate, bits per symbol, and phy layer overhead. Two of these parameters (phyDataRate, phyBitsPerSymbol) are crucial in determining correct

timing in the MAC *so they are left without defaults*. The user has to define them in the .ini file according to the radio chosen. Finally we have a parameter to help us with time-sync:

```
double guardTime = default (1);
```

A guard time is essential when we are dealing with time synchronization. The standard surprisingly does not include such a notion. We have implemented appropriate guard times in various functions of the protocol and this parameter controls the duration (in msecs).

4.3.4 Baseline BAN MAC

Body Area Networks is a fast evolving field of low-power wireless sensor networks. We put considerable effort in making Castalia a simulator suitable for BAN, and the MAC is one important area we focus. The BaselineBANMac module is our implementation of the IEEE 802.15.6 draft proposal for a standard in BAN MAC [8]. It is suggested you read the proposal to get an understanding of the MAC.

You can find the module description in:
`src/node/communication/mac/baselineBanMac/BaselineBANMac.ned`

The first 4 parameters defined are the usual MAC ones, defining buffer size, max packet size and mac packet overhead. Then we have 12 BANMAC-specific related parameters and 5 more parameters that are dependent on the PHY layer but the MAC needs to know about them, and has to define them as its own parameters. Here they are in detail:

```
bool isHub = default(false);
```

Is the node a hub (coordinator device)?

```
double allocationSlotLength = default(10);
```

Defines the length of the basic allocation slot in msecs

```
int beaconPeriodLength = default(32);
```

Defines the beacon period length in allocation slots

```
int RAP1Length= default(8);
```

Defines the Random Access Period length in slots

```
int scheduledAccessLength = default(0);
```

The slots asked by a sensor node from the hub to be assigned for scheduled access

```
int scheduledAccessPeriod = default(1);
```

If asking allocation slots for scheduled access, how often (in beacon periods) is the scheduled access requested for.

```
int maxPacketTries = default(2);
```

The maximum number of tries a packet will be attempted for successful reception.

```
double contentionSlotLength = default(0.36);
```

The length in msecs of the mini-slots used in contention

```
bool enhanceGuardTime = default(false);
```

The draft proposal suggests guard times to account for worse cases of de-synchronization among the nodes. However we discovered that while ending a TX we should really guard for 2GT instead of GT. This variable allows the more conservative guard time to be used.

```
bool enhanceMoreData = default(false);
```

If this variable is true then the moreData flag of the protocol carries information on how many more packets are waiting in the buffer to be transmitted, not just if there are more packets to transmit.

```
bool pollingEnabled = default(false);
```

A variable to control whether polling will be attempted.

```
bool naivePollingScheme = default(false);
```

A variable controlling how polling will be performed

The next 5 parameters are related to the PHY layer. As the proposal suggests we define them as MAC parameters to show the direct connection to the radio.

```
double pTIFS = default(0.03);
```

The time in msecs, to start TXing a frame after you received one

```
double pTimeSleepToTX = default(0.2);
```

The time in msecs, to start TXing after being sleeping. NOT included in spec.

```
int phyLayerOverhead = default(6);
```

The overthead the radio adds in bytes

```
double phyDataRate;
```

Radio’s datarate in Kbps. Notice how there is no default value. As with the 802.15.4 MAC this parameter is crucial in determining correct timings and we do not want the risk of leaving it defined to a wrong value. The user has to explicitly define it in every omnetpp.ini file.

```
double mClockAccuracy = default(0.0001);
```

The clock drift of the node's clock in parts per unit of time. Default is equal to 100ppm (parts per million)

4.4 Routing

Routing in Castalia receives less attention compared to other communication modules. Even though the routing layer enjoys a similar level of abstraction for defining your own protocol as other layers (e.g., App, MAC) there are fewer protocols implemented and released with Castalia. This is due to our own research needs which do not focus on routing, so naturally there is less routing support in Castalia. However, we do acknowledge the need for routing and we do provide all the infrastructure for that layer and a simple routing protocol to use (called multipathRings). We are hoping that in the future, via contributions of external parties we will be able to release the popular Collection Tree Protocol (CTP). Castalia's first support for routing came with release 1.2. In 1.3 we released two routing protocols `simpleTreeRouting` and `multipathRingsRouting` which remained active until version 2.3b. After the major redesign of Castalia in version 3.0 multipathRings was almost written from scratch and simpleTree was not included, since it needed major refactoring. In Castalia 3.2 we still only provide multipathRings and bypassRouting (a module that as the name suggests does not implement any routing).

All routing modules share 4 parameters inherited from the iRouting.ned interface and functionality inherited from the VirtualRouting class. The 4 parameters are:

1) `collectTreceInfo` is the standard parameter we find in all Castalia modules,
2) `maxNetFrameSize` determines the maximum packet size the routing can handle (0 or less means no limit),
3) `netDataFrameOverhead` sets the overhead added to application packets,
4) `netBufferSize` specifies the size of the buffer found in the module.

BypassRouting does not define any new parameters. multipathRingsRouting defines two new parameters on top of the standard four. Let us describe the basic way that multpathRings works.

In multipathRingsRouting nodes do not have a specific parent. A node just gets a level number (or ring number) during setup. The first setup packet sent from the sink has level 0. Any node that receives it adds 1 to the level and retransmits it. The process continues with every node adding 1 to the level of the received packet. Eventually all connected nodes will have a level number (there is also a possibility for unconnected nodes). When a node wants to send a packet to the sink it does not send it to a particular node but rather broadcasts it,

attaching its level number. Any node with a smaller level number will rebroadcast it. The process continues until the sink is reached. You can see with this algorithm many paths to the sink can be taken. The algorithm can be more robust compared to single route algorithms but if the traffic is passes a certain low threshold, congestion can kill performance.

How is a sink node defined? We could define a parameter in the routing module that gave the IDs of sink nodes. We have to question though: is this the job of the routing module? No. Whether or not a node is a sink node depends on the *application*. The application should know where the info should end up. Several applications already in Castalia are defining a parameter called `isSink`. The parameter takes values true/false and is defined for every node (as every node has an application module). MultipathRings looks at this application-level parameter to determine if the node is a sink node and whether the routing module at that particular node should start setting up the routing rings. Thus, if you are using multipathRings, your application should also define the `isSink` parameter. If you are defining your own routing module, you are of course free to change this dependency, but have in mind that routing modules normally do take input from the application.

These are the two extra parameters that multipathRings defines:

```
int mpathRingsSetupFrameOverhead = default (13);
```

The size of a specific control message to setup the rings

```
int netSetupTimeout = default (50);
```

Specifies a timeout when the setting up of the network tree (or level information) is taking place. If a particular node does not receive timely information it might declare it self “not connected” and reports this to the application with a message.

With routing modules infrastructure we also specified a generic format for the network frame. This includes header information: source (string), destination (string), and applicationID (string). A string was chosen to allow the most flexibility in defining destinations and sources. For example, routing protocols could have the following destinations: sink1, parent, point(23,56), areacircle(12, 35, 5), arearectangle(0,0 10, 40). MultipathRings only supports the destination “SINK” (which is also defined as the macro SINK_NETWORK_ADDRESS in CastaliaMessages.h).

4.5 The Physical Process

Sensing is usually neglected in WSN simulators. The usual practice is to feed random numbers to nodes, or each node to have a static value. Issues like sensing device noise or bias are rarely taken into account. In Castalia we tried to go a couple of steps further than the usual practice and capture some essential elements of sensing.

The usual practice to sensed-data generation is to feed random numbers to nodes, or each node to have a static value, or at the best case feed the nodes with traces of sensed data. The last case is indeed realistic if we are concerned with a very specific physical process but the data traces rarely lend themselves to every kind of physical process simulation. For early phase algorithm design we need physical process models that are flexible enough yet have some correspondence to real processes (e.g., spatial correlation of data, variability over time). For this purpose we created a generic physical process model in Castalia to feed the sensing devices of the nodes with data.

4.5.1 Customizable Physical Process

The model is based on an arbitrary number of point sources whose "influence" is diffused over space. A source can change in time and space, i.e., change their position and their value over time. The effect of multiple sources in a certain point is additive. More specifically, the equation that determines the value of the physical process at a certain location and at a certain time is:

$$V(p,t) = \sum_{all\ sources\ i} \frac{V_i(t)}{(K \cdot d_i(p,t) + 1)^a} + N(0,\sigma)$$

Where: $V(p,t)$ denotes the value of the physical process at point p, at time t

$V_i(t)$ denotes the value of the i^{th} source at time t

$d_i(p,t)$ denotes the distance of point p from the i^{th} source at time t

K, a are parameters that determine how is the value from a source diffused.

$N(0,\sigma)$ is a zero-mean gaussian random variable with standard deviation σ

K, a and σ are regular Castalia parameters:

```
double multiplicative_k = default (0.25);
double attenuation_exp_a = default (1.0);
double sigma = default (0.2);
```

$V_i(t)$ and $d_i(p,t)$ are not directly given but they are calculated by the way we describe the behaviour of the sources. We can define up to 5 sources. The number of active sources is defined by the parameter:

```
double numSources = default (1);
```

The behaviour of the sources (i.e., how they change in space and time) is described by the following string parameters:

```
string source_0 = default("0 10 10 30.5; 5 10 10 45; 12 10 10 7.3");
string source_1 = default ("");
string source_2 = default ("");
string source_3 = default ("");
string source_4 = default ("");
```

A string describing a source is of the form: "time pos_x pos_y value; time pos_x pos_y value; time pos_x pos_y value; …"

Each one of the tuples (time, pos_x, pos_y, value) is called a snapshot of the source. The following parameter defines the maximum number of snapshots a source can have:

```
double max_num_snapshots = default (10);
```

To get an idea of the complex and interesting behaviour you can model with this generic model you can view the following video:

http://www.youtube.com/watch?v=cwdK3XdoNF4

The visualization (created with MatLab) shows the evolution of a physical process with two sources that are moving in a 2D field and are changing their values out of phase.

Whereas this model is useful, there are times the user needs to have a much easier (and usually simple and static) control on the values fed to the sensing devices. For example, in the value propagation application we want one or a few nodes to get a value beyond a threshold. Although this can be done with the generic model described above, it requires some calculations in order to determine the right parameters. There is no need to burden the user in such a way. It would be much easier if the user could directly specify the values that nodes should take. Acknowledging this need we allow the user to directly assign the values that the nodes are sensing. The following parameter determines whether the physical process will be described by the model given above or by direct assignment:

```
double inputType = default (1);
```

The default value of 1 means that the physical process is determined by the generic module. A value of 0 means that we will have direct assignment. In that case the values are assigned according to this parameter:

```
string directNodeValueAssignment = default ("(0)");
```

This parameter is a string and its syntax is the following: "(default_value) nodeID_A:value_A nodeID_B:val_B …". That is, nodes that their ID is mentioned in the string are taking the value associate with this id, and nodes not mentioned are just taking the default value. For example, if we have the string "(0) 6:40" all nodes will receive the value 0 except node 6 which will receive value 40. Note here that these values are static, so the value returned is not dependent on the time the node asks a value from the physical process.

4.5.2 Cars Physical Process

The CarsPhysicalProcess models the behaviour of cars passing along a certain distance of the road (for example a bridge). Cars are simulated as sources of abstract sensor readings that can be picked up by wireless sensor nodes. Additionally, each reading is dispersed in the simulated space according to the same formula as in CustomizeablePhysicalProcess where the multiplicative constant K is set to 0.1 and the attenuation constant A is set to 1.

The following parameters are supported:

```
int max_num_cars = default (5);
```

Maximum number of cars that will ever be present at once on the road

```
double car_speed = default (16.0);
```

Car movement speed (in m/s), speed is the same and constant for all cars.

```
double car_value = default (30.0);
```

The value V in the dispersion formula used

```
double car_interarrival = default (20);
```

Average amount of time, in seconds, before a new car appears on the road. Car interarrival times are exponentially distributed.

The road itself is specified in the simulation space by two points, given by their x and y coordinates. These points are set by the following 4 parameters of the module: (point1_x_coord, point2_x_coord, point1_y_coord, point2_y_coord). Each time a car needs to appear, it is randomly assigned to travel either from point 1 to point 2 or the opposite direction. Both cases have equal probability (50%). Once the destination is reached, the car

disappears from the simulation field. Note that points 1 and 2 can lie outside of simulation space, as it does not matter for the module's calculations, which are based purely on distance.

4.6 The Sensor Manager

The “ground truth” offered by the physical process is distorted by the inaccuracies of the sensing devices. In Castalia we offer a set of parameters to model this distortion. Before elaborating in the specifics of each parameter we would like to say a few words on how sensing devices are tied to the physical processes.

In Castalia, there is a one-to one correspondence between sensing device type and a physical process module. This might seem limiting as in reality a single physical process could trigger sensing devices of several modalities. For example, an explosion might trigger microphones, light sensors and temperature sensors. Furthermore, a sensor can be affected by multiple distinct physical processes (e.g., a temperature sensor can be affected by climatic conditions + a nearby fire). Although we acknowledge these interconnections we decided to go for a simpler representation and implementation hoping that it will still cover many practical needs. You probably noticed in the description of the physical process model that we support only one output per point per time (i.e., one type of value, one sensing modality). Similarly there is no way for a sensing device to connect to more than one physical process module. So a more accurate name for the physical process module would be “overall physical process influence to sensing modality X” module. For most practical purposes this will represent an influence from a single physical process (e.g., a nearby fire will be much more important than climatic conditions to a temperature sensor). This one-to-one correspondence does not limit the user to one modality or one physical process, it just makes the code less modular when there are complex interactions.

After this long parenthesis we are ready to look at the parameters Castalia offers for the sensing device:

```
int numSensingDevices = default (1);
```

The number of different sensing device types we have at a node.

```
string sensorTypes = default ("Temperature");
```

String with the names for each of the different sensing device types (space separated)

```
string pwrConsumptionPerDevice = default ("0.02");
```

String-array with the power consumption per sample (in mJoules) for each sensing device (space separated).

```
string corrPhyProcess = default ("0");
```

String-array that holds the index of the Physical process that each one of the sensing device type corresponds (space separated).

```
string maxSampleRates = default ("1");
```

String-array that holds the maximum samples per sec rate for each if the sensing device types (space separated).

```
string devicesBias = default ("0.1");
```

String-array with the sigmas of the bias for each one of the sensing device types. So if the bias sigma is 3 for the temperature sensors then each time we instantiate a new temperature sensor we draw from a normal distribution with sigma 3 in order to find the constant bias of this particular device.

```
string devicesNoise = default ("0.1");
```

String-array with the sigmas of the noise for each one of the sensing device types. So if the noise sigma is 1 for the temperature sensors, each time we get a sample from a temperature sensor (not just when we instantiate one device as above) we add noise drawn from a normal distribution with sigma 1.

```
string devicesSensitivity = default ("0");
```

String-array with the minimum value each device can sense and return

```
string devicesResolution = default ("0.001");
```

String-array with the resolution of discrete readings each device can return.

```
string devicesSaturation = default ("1000");
```

String-array with the maximum value each device can return

```
string devicesHysterisis = default ("");
string devicesDrift = default ("");
```

Not implemented yet.

4.7 The Mobility Manager

The mobility module specifies how the nodes move through space. It holds location state that other modules can access at any time using a function call, and it also notifies the wireless channel periodically of the position of a node. The notification of the wireless channel is done for efficiency reasons. Since the wireless channel needs the location of all nodes very often (every time we have the start of a packet transmission or carrier sensing), it would be detrimental to speed if it had to explicitly ask for the locations of all nodes (only to find out that in most cases nothing changed). It is far better for the mobility module to notify the channel if something changed (for example it could notify it, when the node has just changed cells). However calculation of cell changes can be difficult and do not necessarily need to be part of the Mobility module, thus we give the much simpler (but still efficient) option or periodic updates.

We have defined a virtual mobility module that all other mobility modules should be derived from. It has two parameters:

```
SN.node[*].MobilityManager.collectTraceInfo
SN.node[*].MobilityManager.updateInterval
```

We also have an extra parameter in the node to define the name of the mobility module it is using (much like we do for the application module):

```
SN.node[*].MobilityManagerName
```

Currently we have only implemented one mobility pattern module, the simple `LineMobilityManager`. The user just describes the destination point of a line segment (starting point is the starting location of the node) and thus defines a trajectory for the node to move back and forth. The user also defines the speed that the node is moving. These are the parameters that do that:

```
SN.node[*].MobilityManager.xCoorDestination
SN.node[*].MobilityManager.yCoorDestination
SN.node[*].MobilityManager.zCoorDestination
SN.node[*].MobilityManager.speed
```

If you want to create your own Mobility module(s) with more advanced mobility patterns then read Chapter 5.

4.8 The Resource Manager

The resource manager module keeps track of the energy spent by the node and also holds some node-specific quantities such as the clock drift and the baseline power consumption (you can think of this as the minimum power that the node consumes). There are some provisions to track memory or to define different power consumptions for the processor but they are not fully operational. Modules that model hardware devices (i.e, the radio and the sensor manager) send messages to the Resource manager in order to signal how much power they currently draw. The resource manager then has a complete view of the total power drawn and based on this it calculates energy consumed each time we have a change in power or periodically (if a power change has not happened for some time). The periodic energy consumption calculation is done based on this parameter:

```
double periodicEnergyCalculationInterval = default (1000);
```

We also have a baseline power consumption as we mentioned, given by:

```
double baselineNodePower = default (6);
```

Currently, apart from this constant power draw, only the radio draws power (the sensor manger has not been adjusted to the new power-drawn messages model and requires some remodeling to do so). The initial energy budget of a node is given by:

```
double initialEnergy = default (18720);
```

18720 Joules is the typical energy of two AA batteries. Energy is linearly subtracted based on overall power drawn and time passed, however based on the power-drawn messages modeling we can have more advanced energy consumption models, that take into account the history of power drawn to determine the energy left in battery cells.

Finally, the node clock drift is stored at the resource manager and can be acquired by calling the public method getCPUClockDrift(). The drift is determined by drawing from a zero-mean Gaussian random variable. The sigma is given by the parameter:

```
double sigmaCPUClockDrift = default (0.00003);
```

The drift is actually capped to $\pm 3 \cdot \text{sigma}$ (so it is a capped Gaussian we are drawing from). You can think of the cap as part of the quality assurance these clocks/quartzes undergo. If left uncapped, it is very probable to get 1-2 very large drift values for some seeds/cases (when we run thousands of simulations) which might result in some MAC protocols not working properly for these seeds/cases.

5 Creating your own Application, Routing, MAC, and Mobility Manager modules

So far you have seen and hopefully familiarize yourself with the basics of Castalia. You know how to run simulations, view the output, understand the functionality of different modules and their parameters. You can indeed create a wide variety of simulations based on the available modules. But what if you need to introduce your own distributed algorithm in Castalia by introducing your own application module? What if you want to implement a new MAC protocol or a new Routing protocol? How about implementing a Mobility Manager that supports new mobility patterns? Castalia has provisions that make the creation of any of these four kinds of modules easier. We will start by giving general instructions that apply to all 4 kinds of modules and then we will see some issues that relate to each kind separately.

The first step is to determine the correct location for the new code within the Castalia directory structure and create a dedicated directory to hold the source code of the new module. The correct locations are:

for Application: `src/node/application/`

for Routing: `src/node/communication/routing/`

for MAC: `src/node/communication/mac/`

for mobility: `src/node/mobilityManager/`

Each of these directories already includes several subdirectories that contain various implementations of relevant modules. After a directory for the new module is created, it is necessary to define that module using the NED language (i.e. create the module's .ned file). This file is created inside the module's dedicated directory and is named using the new module's name. Assume that the new module to be created is called “NewCastaliaModule”. Following OMNeT’s naming convention; the dedicated directory for this module should be named `newCastaliaModule` - i.e. starting with lower case letter. In this directory we need to create the file `NewCastaliaModule.ned`. First thing in this file is the definition of the package of the module. The package can be obtained by taking the path to the .ned file relative to the Castalia's `src/` directory, and then replacing '/' symbols with '.'. For example, if NewCastaliaModule is a MAC module, then the package in NewCastaliaModule.ned file will be declared as:

```
package node.communication.mac.newCastaliaModule;
```

Next step is to define the module itself. Here we note that the module's parent directory contains a .ned file that has a name starting with the letter 'i'. This is the *interface file* that has to be followed in order for the new module to fit into the structure of Castalia. For NewCastaliaModule to be recognized as a Castalia MAC, it has to be declared using the 'like' keyword, referencing the interface module. That is:

```
simple NewCastaliaModule like node.communication.mac.iMac
```

Next comes a list of parameters that will be passed to the module at runtime from the simulation configuration. Each interface .ned file will already include a set of parameters that are mandatory for all MAC modules, however new parameters can be included. Below is a full example of NewCastaliaModule.ned file:

```
package node.communication.mac.newCastaliaModule;
simple NewCastaliaModule like node.communication.mac.iMac {
	parameters:
		bool collectTraceInfo = default(false);
		int macMaxPacketSize = default(0);
		int macBufferSize = default(16);
		int macPacketOverhead = default(8);

		int newParameter1;
		string newParameter2 = default("default value");
		bool newParameter3 = default(false);
	gates:
		output toNetworkModule;
		output toRadioModule;
		input fromNetworkModule;
		input fromRadioModule;
		input fromCommModuleResourceMgr;
}
```

The first four parameters are defined in the iMac.ned interface file and are mandatory. Each interface file will have its own set of mandatory parameters that will vary depending on which module is being created. After the mandatory parameters for a MAC there are 3 parameters *specific* to NewCastaliaModule. Note that it is possible to provide default values for parameters (even for mandatory parameters from the interface). If a default value is not given, then the parameter *has to be assigned* a value in the configuration input file (omnetpp.ini).

Gates are fully defined by the interface .ned file and have to match exactly (i.e. 'gates:' section can be entirely copied from interface file). This concludes the definition of the .ned file.

The next step is to write the actual code of the module. A module it represented by a C++ object, and it has to inherit from appropriate base classes that are provided (or as we call them Virtual classes[14] to show that they cannot instantiate modules on their own, at least one of its methods has to be defined). These Virtual classes are the main help Castalia offers in defining new modules. A developer can (and strongly suggested to) use the methods and structure already defined by these Virtual classes.

For our current example it is necessary to create the files NewCastaliaModule.h and NewCastaliaModule.cc. In the .h file we declare a new C++ class that will implement our module. The name of the class has to match the name of the module and the name of the .ned file. As we already mentioned, the class inherits from one of the virtual classes we provide according to the kind of module we are creating.

For Application:	`class NewCastaliaModule : public VirtualApplication{`
For Routing:	`class NewCastaliaModule : public VirtualRouting {`
For MAC:	`class NewCastaliaModule : public VirtualMac {`
For MobilityManager:	`class NewCastaliaModule : public VirtualMobilityManager{`

In the .cc file we first include the .h we just created and then we call the Define_Module macro to register our new creation as an OMNeT module:

```
Define_Module(NewCastaliaModule);
```

After this we have to define (or redefine) the methods that the virtual class declares/defines. The methods depend on the kind of module we are implementing and thus we will see them in separate sections.

After you are done with all the new files creation, remember to rebuild Castalia using the following commands from the top-most Castalia directory.

```
Castalia $ make clean
Castalia $./makemake
Castalia $ make
```

14 Not to be confused with “virtual classes” in OOP. These are regular base classes (aka super classes, or parent classes) in the OOP sense which have several virtual methods.

If you are using any external libraries, consult the last section of the Installation Guide to find out how to include them in the build process.

5.1 Collecting Output and Defining Timers

All of the Virtual classes (i.e., VirtualApplication, VirtualRouting, VirtualMac, VirtualMobilityManager) share two parent classes: `CastaliaModule` and `TimerService`. These parent classes offer services to collect output and define timers. Let us see on how we collect output first.

5.1.1 Collecting Output

You have already seen from chapter 3 that output is given in specially formatted files which CastaliaResults parses, process and aggregates so it can present to the user relevant information. The output is written in these files with the use of methods defined in the CastaliaModule class. These methods can be used in any Castalia module (i.e., in the C++ code that defines the module) since all classes that define modules are derived from `CastaliaModule`. There are currently two types of output: 1) simple output and 2) histogram. In its simplest form the simple output is just one number: for instance, the consumed energy from one node. In a more complex form it can be several numbers each associated with a label. For example, the output “Radio packet breakdown” can have up to 6 labels such as: “Success, with interference”, “Success without interference”, “Fail, with interference”, “Fail, without interference”, “Fail, below sensitivity”, “Fail, wrong state”. In this case, the number associated with each label reports the number of packets that are described by this label. In the most complex form a “simple output” can also have an index. For example, at the application ThrouputTest we use an index to differentiate between packets received by different sources. A histogram on the other hand is an array of numbers that represent the counts for equally-spaced buckets between a min and a max value. A histogram can also have an index (although we have not used this feature in the code yet).

Let us see what methods are there for the simple output case. To start collecting output we first need to declare the output name.

```
declareOutput(“appropriate name for the output”);
```

This method declares a new output by its name. Then we can use the name to collect output using the following method:

```
collectOutput(“output name”, index, “label”, amountIncreased);
```

This method adds the amountIncreased double number to the value of the output name with a certain label and index. The method is overloaded so you can use it in different forms without having to define all the arguments. For instance:

```
collectOutput(“output name”);
```

Adds 1 to the single value of output name.

```
collectOutput(“output name”, 3);
```

Adds one to the value of output name **with index** 3.

```
collectOutput(“output name”, “units”);
```

Adds one to the value of output name with label “units”

```
collectOutput(“output name”, “”, 25.3);
```

Adds 25.3 to the value of output name. Note how we use an empty string if the output does not have distinct labels (otherwise we would put the name of the label there). Not using the empty string would result in a mistake, or even worse, if the value is integer (e.g. 25), it would result in adding 1 to the output name with index 25 (see above overloaded definition).

When the simulation ends the values from all outputs of a module are written to the output file keeping information on what module produced this output.

Moving on, let us look at the histogram case. We start by declaring a histogram, giving its name, the min value, the max value and the number of buckets.

```
declareHistogram(const char *, double, double, int);
```

Then we can use this method to update the histogram

```
collectHistogram(“histogram name”, value);
```

This will look at the value, figure out which bucket it belongs too and add one count to that bucket.

We can also call the above method with an index argument

```
collectHistogram(“histogram name”, index, value);
```

We will see some examples of using collectOutput in section 5.2.1

5.1.2 Defining and Using Timers

Timers are another important feature of Castalia. It is essential for the app/mac/routing developer to be able to define timers and act when they expire. A developer

could achieve this functionality by using OMNeT's self messages. This solution is not desirable though. Apart from expanding the type of messages in an ad-hoc way (which would be hard to handle in the Virtual classes) the clock drift of each node is not taken into account. Instead, we provide a service to set, get, cancel, and react to timers, taking into account the individual node drifts, while providing a clean and easy interface to the user. There are a few methods to act and react to timers. First we can set a timer:

```
setTimer(index, time);
```

The index is just an integer and the time is just a double-typed value. It is a good idea to name the different indexes in an enum structure. For example Throughput application defines just one timer in its .h file:

```
enum ThroughputTestTimers {
      SEND_PACKET = 1
};
```

It is also a good idea to name the timers with names that describe the action taken when the timer expires, or describe the event that happened (e.g., ACK_TIMEOUT). Once you set a timer, it is active. When it expires it will create an event. The event will trigger the calling of this method with the index of the expired timer as the argument:

```
timerFiredCallback(index);
```

The developer then has to define this method in the new app/mac/routing module, usually with a big switch statement. The switch statement look at the index and depending on which timer expired acts differently. Look for instance how TunableMAC.cc defines its timerFiredCallback(). Once a timer expires it stays inactive until it gets set again.

The user can also get the time value of an active (or not active) timer. If the timer is not active then 0 is returned.

```
getTimer(index);
```

This is an easy way to check whether a timer is active instead of keeping a separate variable for that purpose.

Finally a user/developer can cancel a timer. Canceling a timer means that you make it inactive without triggering an expiration event.

```
cancelTimer(int index);
```

Using all these timer methods the node clock drift is automatically taken into account.

5.2 Defining a new Application module

The VirtualApplication class defines a base for any Castalia application. It defines the basic methods to operate within the Castalia framework (e.g., process the right messages in a handleMessage method) and defines a set of methods that the *specific application* can use to interact with the rest of the modules. There are two kinds of methods.

1) "Callback" methods that the code in virtualApp calls at appropriate points (when certain events happen) and *the specific application has to define* in order to describe what to do when the event associated to the callback method happens (e.g., receiving a packet from the routing/network layer, or receiving a sensor reading)
2) Methods that are already defined in virtualApp and the specific app can call to perform a certain action (e.g., sent a packet to routing, create an app packet)

Let us see the callback methods first:

```
void startup()
```

This method is called at initialization. You should perform any app-specific initialization actions required by your app. Most usually reading app-specific parameters and assigning them to class variables.

```
void finishSpecific()
```

This method is called in the end of simulation. Most usual actions performed there are: freeing up memory allocated by some app-specific objects, or collecting output specific to that application

```
void fromNetworkLayer(ApplicationPacket *packet, const char *srcAddr,
double RSSI, double LQI)
```

This virtual method is mandatory for the new app module to define. It is called when a packet is received from the communication stack. Its arguments include the packet itself, the RSSI and LQI values for this packet (measured by the radio), as well as the network source address the packet originated (a network address is a string),

```
void handleSensorReading(SensorReadingMessage *)
```

This method is called whenever a sensor reading is returned from the sensing device.

```
void handleNetworkControlMessage(cMessage *)
void handleMacControlMessage(cMessage *)
void handleRadioControlMessage(RadioControlMessage *)
```

These methods allow us to react to control messages from various communication layers.

The rest of the methods that VirtualApp provides can be called from the specific app to perform certain actions.

```
void requestSensorReading(int index)
```

Request a reading from sensor with given index. The result will be returned with the `handleSensorReading` callback method.

```
void toNetworkLayer(cMessage *msg)
```

Send a *control message* to the communication stack. Note that a control message is not a data packet. It is a command to communication layers below. Some examples are: changing the TX power of the radio, or the RX mode, changing a parameter of the MAC (such as the duty cycle), or changing a parameter of the routing protocol. Examples of creating and sending such commands were given is sections 4.2.4 (Radio) and 4.3.1.1 (TunableMAC).

```
void toNetworkLayer(cPacket *pkt, const char *dstAddr)
```

Send a *data packet* to the communication stack, to be delivered to given address. The address is a literal string. For example we can use the macros BROADCAST_NETWORK_ADDRESS or SINK_NETWORK_ADDRESS to either send to all our 1-hop neighbors or to send to the sink node (only if the appropriate routing protocol is used, BypassRouting does not recognize this address). Or the address can simply be the node's ID e.g. `toNetworkLayer(pkt, "4")` sends the packet to node 4. With the current selection of routing modules, the packet in such a case will be delivered only if node 4 is a 1-hop neighbour of the sending node. Otherwise the packet will not reach its destination as neither BypassRouting nor MultiPathRingsRouting know how to find the next hop for arbitrary addresses. The packet will simply be sent to the node with MAC address 4 and if it happens to be in range it will receive it.

```
ApplicationPacket *createGenericDataPacket(double data, int
sequenceNum, int size)
```

Creates an application data packet with a double-type number as data, a sequence number, and an optional size. If the size is not given, then the size of the packet will be determined by the constantDataPayload parameter of the application. You can study how this function is written to find out how to create packets of your own kind. For example you can find out how to set their size in a per packet basis if you need to do so.

We already mentioned in the beginning of chapter 5 that when defining the .ned file of a new module (for the app, routing, mac, mobility) we have to follow an interface .ned. For the case of a new application this is iApplication.ned. There we have 5 generic parameters

that all applications support. The VirtualApplication code parses these parameters and also uses them while performing basic functions. The 5 parameters are:

```
string applicationID;
```

A description and an identifier for the application. The applicationID is used in the virtualApp code to filter packets from different applications (in the case we have more that 2 applications running in the same network). If the applicationID is the empty string “” then there is no filtering done, i.e., fromNetworkLayer() is called for all packets received from the routing layer.

```
bool collectTraceInfo;
```

The standard parameter relating to trace collection that all Castalia modules share.

```
int priority;
```

A priority indication, not currently used.

```
int packetHeaderOverhead;
```

Overhead in bytes that is added to all app packets before going to the routing layer. The overhead is added in the virtualApp code. It applies to both the constant payload case and the case where the size is given by the user for each packet.

```
int constantDataPayload;
```

If a packet’s size is 0 before going to the network layer (if left undefined then the size will be 0) then the packet size is forced to constantDataPayload (and the overhead is added). To set the size of a packet you create you can use the OMNeT function:

```
appPkt->setByteLength(size);
```

or if you are creating a standard/generic application packet you can call `createGenericDataPacket()` with a size number as the 3rd argument.

Finally some tips on commons actions in app. If you need to access the current node’s position from the application module, here is how you can do it:

```
double x_coor = mobilityModule->getLocation().x;
double y_coor = mobilityModule->getLocation().y;
```

If you have mobile nodes remember to read these variables regularly so you have an updated position.

5.2.1 The ThroughputTest application example

Let's look at the already implemented ThroughputTest app module to see how some of these methods are used. Open file src/node/application/throughputTest/ThroughputTest.cc

At the startup method, notice how we read the specific parameters that this app is defining (the generic parameters that all applications share are handled by the VirtualApp code). Notice how we use `trace()` to create trace outputs. Notice also we use `declareOutput()` to name and declare the output that will be produced by this module and processed by the `CastaliaResults` script.

In the `fromNetworkLayer()` callback method we first extract the sequence number from the packet and then check whether our own parameter `recepientAddress` is the same as our own address. If so, the packet has reached the final destination and can be recorded in the output. Otherwise it is forwarded to the recipientAddress. This logic might seem straightforward so let us explain it further. Throughput app can have different recipient addresses at different nodes. In this way the user can create application level static routing chains. For example, if a node has a recipient address of 1, then it will forward the packets it receives and the packets it creates to node 1. The transmitted packets might be received from the radios of multiple nodes, but they will reach the application layer of only node 1 (there is filtering done in other layers). If node 1 has a recipient address 1 (itself) then this is the final destination. If it has a recipient address 0 then the packets received will be forwarded to node 0. So the recipient address at node X, shows the node address to send the packets generated and/or received by the node X.

If the packet reached the final destination, we count it in the received packets. Notice how we use the collectOutput method and how a second int parameter is used as an index to show the source of the packet. We also react to a single timer expiring. Finally we define a specific handleRadioControlMessage() to handle a carrier sense interrupt message (we simply record it in the trace file).

5.2.2 Defining your own application packets

The default application packet in Castalia (called ApplicationPacket) has only one field (type double) to carry data. It is probable that you might want to define a more complex packet for your application. Your first step is to derive your new packet from ApplicationPacket since the latter defines fields that are used by the virtualApp code. Here is how you extend a packet with a simple struct. Create a new .msg file in your application directory with the name of the packet you want to introduce (e.g., MyPacket.msg). These should be the contents of the file:

```
cplusplus {{
#include "ApplicationPacket_m.h"
}}
class ApplicationPacket;
struct info {
      unsigned short nodeID;  //the ID of the Node
      double locX;                  // x-coordinate of the node
      double locY;                  // y-coordinate of the node
}
packet MyPacket  extends ApplicationPacket {
      info extraData;
}
```

You can go much further than adding a struct. OMNeT provides several rich ways to define complex messages and packets. Read section 5.2 of the OMNeT manual:

http://www.omnetpp.org/doc/omnetpp41/manual/usman.html#sec201

In your module's .h file (assuming your app is called MyApp, you should have a MyApp.h) you should include the .h file automatically generated from your .msg:

```
#include "MyPacket_m.h"
```

Then in your application code whenever you need to create a new MyPacket you do:

```
MyPackett *pkt = new MyPacket("my description", APPLICATION_PACKET);
```

And then **you need to set its fields** and possibly its size. For example:

```
      info tmpData;
      tmpData.nodeID = (unsigned short)self;
      tmpData.locX = mobilityModule->getLocation().x;
      tmpData.locY = mobilityModule->getLocation().y;
      pkt->setExtraData(tmpData);
```

You can also set the generic fields of ApplicationPacket (i.e., data, sequenceNumber)

```
      pkt->setData(sensValue);
      pkt->setSequenceNumber(currSentSampleSN);
      currSentSampleSN++;
```

If you need the size to be variable depending on what you include in the packet then you need you set it as well. Otherwise the size will be the constantDataPayload.

```
pkt->setByteLength(mysize);
```

5.3 Defining a new Routing module

The VirtualRouting class defines a base for any Castalia routing module. It defines the basic methods to operate within the Castalia framework (e.g., process the right messages in a handleMessage method) and defines a set of methods that the *specific routing protocol* can use to interact with the rest of the modules. As with the VirtualApplication case there are two kinds of methods: 1) Callback methods that need to be defined by the specific routing protocol to react to certain events, and 2) pre-defined methods that perform generic operations. The callcabks are:

```
void startup()
```

This function is called at initialization. Usually you read parameters specific to your protocol and initialize the state.

```
void finishSpecific()
```

This function is called in the end of simulation. Usually it is not even defined (nothing special to do).

```
void fromApplicationLayer(cPacket *pkt, const char *dstAddr)
```

Reacts to a data packet received from the app (outgoing data packet). This method is mandatory for the new routing module to define. Its arguments include the packet itself and the desired destination address. These are essentially the arguments that the application-level `toNetworkLayer(cPacket *pkt, const char *dstAddr)` uses. The packet should be encapsulated and buffered (there are functions to help you perform these tasks)

```
void fromMacLayer(cPacket *pkt, int srcMacAddress, double RSSI,
double LQI)
```

Reacts to a data packet coming from the MAC (incoming data packet). This method is mandatory for the new routing module to define. Its arguments include the packet itself, the mac address of the node that sent this packet (last hop), plus RSSI and LQI information on the received packet. The packet should be examined and if it is a data packet (not routing control packet) it should be forwarded, or discarded, or decapsulated and passed to the application.

```
void handleNetworkControlCommand(cMessage *)
```

Reacts to messages of type NETWORK_CONTROL_COMMAND. These messages are defined to change some operational parameters of a routing protocol. You have to define the messages in more detail and also define this method to get the desired control effect. Usually the application layer would issue these messages, but it could also come from below (MAC). Note to avoid confusion: these are messages sent from either the app or the mac modules of

the same node, to the routing module to affect its behaviour; they are not routing control packets exchanged between different nodes. Routing control packets are of the regular NETWORK_LAYER_PACKET type.

```
void handleMacControlMessage(cMessage *)
```

React to a control message coming from the MAC. For example, the MAC might notify us that its buffer is full. The default action is to forward these messages to the application, but you can redefine the method to handle them as you wish.

```
void handleRadioControlMessage(cMessage *)
```

React to a control message coming from the Radio. For example, the Radio might send a carrier sense interrupt (that the MAC has forwarded). The default action is to forward these messages to the application, but you can redefine the method to handle them as you wish.

The rest of the methods that VirtualRouting provides can be called from the specific protocol to perform certain actions (i.e. can be called from the module's code):

```
void encapsulatePacket(cPacket *, cPacket *)
```

Encapsulates an application packet in a routing packet and sets the different RoutingPacket fileds to the appropriate values. Used in your fromApplicationLayer(). As a principle call encapsulatePacket() before your own modifications to the routing packet fields.

```
int bufferPacket(cPacket *pkt)
```

After an app packet has been encapsulated, it will store that packet in the buffer. Used in your fromApplicationLayer(). If the buffer is full, it will automatically create and send control message to the application.

```
cPacket *decapsulatePacket(cPacket *)
```

Decapsulates routing packet to extract application packet, and sets appropriate fields in that packet (RSSI, LQI, source)

```
void toApplicationLayer(cMessage *msg)
```

Sends control messages and packets to the application layer.

```
void toMacLayer(cMessage *msg)
```

Sends *control message* to MAC layer. Notice the diffent method to send packets.

```
void toMacLayer(cPacket *pkt, int macAddr)
```

Sends a *packet* to MAC layer, along with the destination MAC address. The MAC destination is essentially the next hop. The routing protocol will decide on the next hop based on the

information it has. The next hop address will be in a string format (routing address). The MAC address has to be an integer and the method below can help with the conversion.

```
int resolveNetworkAddress(const char *)
```

Converts Network layer address to MAC layer address

```
bool isNotDuplicatePacket(cPacket *pkt)
```

This method performs a valuable test. It checks whether this packet has been seen before (extracting the source address and sequence number). It can be used to avoid senfind duplicate packets to the application layer.

5.3.1 BypassRouting module

Let us see how the BypassRouting module is implemented. Bypass is the simplest possible routing module, without any actual multi-hop routing functionality. Nevertheless it performs some basic filtering.

We define only the two mandatory methods. fromApplicationLayer() and fromMacLayer().

fromApplicationLayer() defines a new BypassRouting packet, sets the source and destination addresses, encapsulates the application packet and sends the newly form packet to the MAC layer. Notice how we use resolveNetworkAddress() to do the needed conversion before using toMacLayer().

fromMacLayer() casts the packet received to the most generic routing packet. If the cast is successful then it checks the destination address of the received packet. If the destination address is this node, or the destination address is a broadcast then this packet should be sent to the application level. Otherwise it is discarded. Notice how the packet is decapsulated before using toApplicationLayer() to sent it to the application.

5.4 Defining a new MAC module

The VirtualMac class defines a base for any Castalia MAC module. It defines the basic methods to operate within the Castalia framework (e.g., process the right messages in a handleMessage method) and defines a set of methods that the *specific MAC protocol* can use to interact with the rest of the modules. As with the VirtualApplication and Virtual Routing cases there are two kinds of methods: 1) Callback methods that need to be defined by the specific MAC protocol to react to certain events, and 2) pre-defined methods that perform generic operations. The callcabks are:

:

```
void startup()
```

This function is called at initialization (similar to the other virtual cases).

```
void finishSpecific()
```

This function is called in the end of simulation (similar to the other virtual cases).

```
void fromNetworkLayer(cPacket *pkt, int dstAddr)
```

Reacts to a data packet received from the routing layer (outgoing data packet). This method is mandatory for the new MAC module to define. Its arguments include the packet itself and the desired destination address.

```
void fromRadioLayer(cPacket *pkt, double RSSI, double LQI)
```

Reacts to a data packet received from the Radio (incoming packet). This method is mandatory for the new MAC module to define. Its arguments include the packet itself and RSSI and LQI information associated with that packet.

```
int handleControlCommand(cMessage * msg)
```

Reacts to messages of type MAC_CONTROL_COMMAND. These messages are defined to change some operational parameters of a MAC protocol (e.g., dutyCycle in TunableMAC). You have to define the messages that your MAC will accept, and also define this method to get the desired control effect. Usually the application or the routing layer would issue these messages.

```
void handleRadioControlMessage(cMessage *)
```

React to a control message coming from the Radio. For example, the Radio might send a carrier sense interrupt. The default action is to forward these messages to the routing layer, but you can redefine the method to handle them as you wish.

The rest of the methods that VirtualMAC provides can be called from the specific protocol to perform certain actions (i.e. can be called from the module's code):

```
int bufferPacket(cPacket *pkt)
```

Stores an incoming data packet in the buffer.

```
void toNetworkLayer(cMessage *msg)
```

Sends packet/message to Routing layer.

```
void toRadioLayer(cMessage *msg)
```

Sends packet/message to Radio.

```
void encapsulatePacket(cPacket *, cPacket *)
```

Encapsulates a routing packet in a MAC packet. This should be done **before** you set the MAC packet fields in a protocol-specific way. For example if you are setting the destination address of a MAC packet you should do it after encapsulatePacket() since encapsulatePacket sets the destination field to BROADCAST_MAC_ADDRESS.

```
cPacket *decapsulatePacket(cPacket *)
```

Decapsulates MAC packet to extract routing packet

```
bool isNotDuplicatePacket(cPacket * pkt)
```

Checks whether this packet (sequence number from the same sender) was received before.

Let's look at TunableMAC to see how these methods are used more concretely.

5.4.1 The TunableMAC module example

TunableMAC is a non-trivial MAC implemented in Castalia, allowing many of its operational parameters to be tuned as we saw in section 4.3.1. Its design required considerable experimentation and experience (TunableMAC changed over the years). We will not discuss here the how of the design -this is a bigger discussion- but we will use it as an example to showcase how a specific MAC is implemented using the VirtualMAC provisions. The file `src/node/communication/mac/tunableMac/TunableMAC.h` contains some basic information on the MAC structure, defining the name for its states, timers, other enums (e.g., backoff types) and the class variables and methods. The code is of the MAC is in:

`src/node/communication/mac/tunableMac/TunableMAC.cc`

The `startup()` method initializes the class variables, by mostly reading the parameters of the omnetpp.ini file. Notice also how we set the radio to listen/RX mode (in case it is not by default) with the statement:

```
toRadioLayer(createRadioCommand(SET_STATE, RX));
```

Also notice how we set our first timer (if duty cycling is enabled):

```
setTimer(START_SLEEPING, listenInterval);
```

The `timerFiredCallback()` method which reacts to timers expiring, handles all 5 timers in a simple and straightforward way (this is part of our design methodology). The timers are defined in a such a way so as to execute a specific operation when they expire (their name too reflects the operation to be done when they expire). Notice for example how the first 3 timers put the radio in a specific state. Also note that the first two timers set other timers as part of their expiration action.

Then we define the `handleCarrierSenseResult()` method which as the name suggests reacts to the result of carrier sensing, i..e, directly asking the radio if the channel is below or above the channelClear threshold by calling `radioModule->isChannelClear()`. The method is essentially a big switch statement that handles the 4 different types of outcome (CS_NOT_VALID and CS_NOT_VALID_YET are handled the same way).

Then we define the `fromNetworkLayer()` method (this is one of the virtual methods of the base class VirtualMAC that has to be defined by our specific MAC). You see how we define a new TunableMAC packet, encapsulate the network packet into it, and **then**[15] set some fields of the MAC packet. We then buffer the packet and depending on state and buffer size we can take further actions (i.,e canceling timers and calling attemptTx()).

`attemptTx()` checks the state of retransmissions and the buffer and either starts the timer to start contending, or deletes the current packet and moves for the next one, or goes to sleep (if there is nothing to TX).

`sendBeaconsOrData()` send the actual beacons or data packets to the radio and waits till it tries again (by settting a timer that will call the same function when expires). The comments should help you follow the logic of the code there.

Then we have `fromRadioLayer()` the other method that has to be defined by a specific MAC. We begin by making some basic filtering. First, we cast the packet to TunableMacPacket. If the cast fails this means that the packet is from another MAC and can be ignored. Then we look at the destination. If the destination it's not this node or not a broadcast then again we filter out the packet. If the packet is for us then we process it according to its type. If it is a beacon packet we change the state of the MAC and cancel the sleeping timer. We also schedule a timer to attemptTx into the future to ensure that eventually we will get back to our normal operation (in the case we do not receive the data, or other events). If the packet is a data packet then we pass to the network layer, decapsulating it first:

```
toNetworkLayer(macFrame->decapsulate());
```

Finally in `the handleControlCommand()` we handle all possible commands we can take. These are commands that change the operating parameters of the MAC.

5.5 Defining a new Mobility manager module

The VirtualMobilityManager class defines a base for any mobility manager module and provides several functions to help with the operations of the module. All mobility manager

15 As noticed before it is important to **first** call encapsulatePacket() and **then** set specific MAC fields, since encapsulatePacket() sets some of the MAC packet fields with default values.

modules should be derived from this base class. However, unlike the app/routing/MAC base classes, which already define OMNeT's `handleMessage`, in a MobilityManager module the user has to define this method. Moreover, if specific initialization or finalization is needed, then the functions `initialize()` and `finishSpecific()` have to be redefined. In other words, here there is no extra layer of abstraction with methods like startup(), fromYYlayer() and timerFiredCallback(). Nevertheless, an `initialize()` method is defined in the base/super class, which defines important common operations, so if you need to define your own initialize then you need to call the base/super class method too. For example in the LineMobilityManager we have:

```
void LineMobilityManager::initialize()
{
      VirtualMobilityManager::initialize();
… // reading specific parameters for the LineMobilityModule
```

Remember whenever you define your own initialize() for your mobility module, make sure you call the super class' method first, before going into your specific code. For specifc finalization you simply define finishSpecific() (declared as part of the CastaliaModule which is the base class for VirtualMobilityManager). In the future this structure might change and make virtual mobility manager to resemble more the other virtual modules.

Functions that are provided from the base class and can be called from the module's code:

```
void notifyWirelessChannel()
```

Notifies the wireless channel about this node's location. Usually you need to periodically notify the channel about the node's position and you can do it by just calling this method. To create the periodic event, you just create a self message in handleMessage() that can be scheduled periodically (see `LineMobilityModule` for example) or more complex patterns can be created if needed.

```
void setLocation(double x, double y, double z)
void setLocation(NodeLocation_type)
```

These methods alter a node's location and automatically notify the wireless channel.

The current node location can be accessed through the protected variable `nodeLocation` of type `NodeLocation_type`

6 Appendix: Full List of Modules and Parameters

In this appendix we provide a full list of modules and a list of the modules' parameters. The lists structure follows the module (and directory) structure in Castalia, starting from the topmost module.

6.1 List of Modules

. The following diagram provides an easy way to see all the modules and also show their hierarchical relations. Note that sometimes a module can be one of several possible similar modules (modules that share a common interface). This happens with modules such as the Application, the Routing, the MAC, and the MobilityManager. For example, we have multiple applications modules that all share the same full hierarchy name: `SN.node[*].Application`. Which of the different application modules we will use depends on a parameter of the node module called `ApplicationName`. ApplicationName gives the name of the NED file that implements the desired application module. In the diagram below, all possible module names are given in curly brackets {}.

SN
- node[*]
  - Application {BridgeTest, ConnectivityMap, ThroughputTest, ValuePropagation, ValueReporting}
  - Communication
    - MAC {BaselineBANMAC, BypassMAC, Mac802154, TMAC, TunableMAC}
    - Radio
    - Routing {BypassRouting, MultipathRingsRouting}
  - MobilityManager {LineMobilityManager, NoMobilityManager}
  - ResourceManager
  - SensorManager
- physicalProcess[*] {CarsPhysicalProcess, CustomizablePhysicalProcess}
- wirelessChannel

6.2 List of Parameters

The only generic OMNeT++ parameter that the user will be interested in setting is `sim-time-limit` (or rarely `cpu-time-limit`, which limits the real cpu time of a simulation). All the rest are Castalia-specific parameters. Parameters are listed per module. First we give the NED file that describes the module and then we give the full hierarchy name to reference the module. Parameters in the module have to be prefixed by the full hierarchy name to be properly addressed in an .ini file. For example the `Radio` module has one parameter called `carrierFreq`, and the full hierarchy name for the module is `SN.Node[*].Communication.Radio`. Thus if we want to change the carrier frequency of all the radios to 1000, the ini file has to include a line: `SN.Node[*].Communication.Radio.carrierFreq = 1000`. Note the use of * to access all radio modules in all nodes. Whenever there is an array of modules we will give the full hierarchy name with a *, but the user is free to make it more specific based on OMNeT++ syntax rules. Note also that some modules share the same full hierarchy name. These are the modules found in curly brackets {} in the previous section. In the parameters list you will see the notation "*(shared)*" next to the full hierarchy name to signify this.

Module NED file: **src/SensorNework.ned**

Full hierarchy name: **SN**

Parameter Name	Default Value	Refer
field_x	30	Section 3.2
field_y	30	Section 3.2
field_z	0	Section 3.2
numNodes		Section 3.2
deployment		Section 3.2
numPhysicalProcesses	1	Section 4.5
physicalProcessName	"CustomizablePhysicalProcess"	Section 4.5
debugInfoFileName	"Castalia-Trace.txt"	below

The debugIfoFileName is a string that gives the filename that all trace output will be written.

Module NED file: **src/node/Node.ned**

Full hierarchy name: **SN.node[*]**

Parameter Name	Default Value	Refer
xCoor	0	below

yCoor	0	below
zCoor	0	below
phi	0	below
theta	0	below
startupOffset	0	below
startupRandomization	0.05	below
ApplicationName		Section 3.2
MobilityManagerName	NoMobilityManager	Section 3.2

`xCoor, yCoor, zCoor, phi, theta` give the initial position and initial orientation of a node. Orientation is not currently being used to affect signal reception at the radio, or in any way, but the parameters exist and are available to be used by applications if needed. `startupOffset` is an absolute offset in seconds for the starting time of a node. `startupRandomization` gives the upper bound of a time interval (in seconds). We draw uniformly from that interval to affect the startup time of a node. Note that this randomly drawn time is added to the offset.

Module NED file: **src/node/application/bridgeTest/BridgeTest.ned**

Full hierarchy name: **SN.node[*].Application** *(shared)*

Parameter Name	**Default Value**	**Refer**
applicationID	“BridgeTest”	Section 5.1
collectTraceInfo	false	Section 5.1
Priority	1	Section 5.1
packetHeaderOverhead	8	Section 5.1
constantDataPayload	0	Section 5.1
isSink	0	Section 3.6.2
reportDestination	“0”	Section 3.6.2
reportTreshold	10	Section 3.6.2
sampleInterval	100	Section 3.6.2
sampleSize	12	Section 3.6.2
reprogramInterval	86400	Section 3.6.2
reprogramPacketDelay	500	Section 3.6.2
reprogramPayload	5120	Section 3.6.2
maxPayloadPacketSize	128	Section 3.6.2

Module NED file: **src/node/application/connectivityMap/ConnectivityMap.ned**

Full hierarchy name: **SN.node[*].Application** *(shared)*

Parameter Name	Default Value	Refer
applicationID	“connMap”	Section 5.1
collectTraceInfo	false	Section 5.1
priority	1	Section 5.1
constantDataPayload	8	Section 5.1
packetSpacing	100	below
packetsPerNode	100	below
packetSize	32	below

PacketSpacing sets the interval between packet transmissions. packetsPerNode defines how many packet will each node transmit, and packetsize is the packet size in bytes.

Module NED file: **src/node/application/throughputTest/ThroughputTest.ned**

Full hierarchy name: **SN.node[*].Application** *(shared)*

Parameter Name	Default Value	Refer
applicationID	“throughputTest”	Section 5.1
collectTraceInfo	false	Section 5.1
priority	1	Section 5.1
packetHeaderOverhead	5	Section 5.1
constantDataPayload	100	Section 5.1
nextRecipient	“0”	Section 5.1
packet_rate	0	below
startupDelay	0	below
latencyHistogramMax	200	below
latencyHistogramBuckets	10	below

The packet_rate sets the rate at which packets are transmitted by each node in packets/sec. The startupDelay sets a delay in secs than the app will start transmitting after the node has been activated. The latency histogram parameters set how the application level latency is to be recorded

Module NED file: **src/node/application/valuePropagation/ValuePropagation.ned**

Full hierarchy name: **SN.node[*].Application** *(shared)*

Parameter Name	Default Value	Refer

applicationID	“valuePropagation”	Section 5.1
collectTraceInfo	false	Section 5.1
priority	1	Section 5.1
packetHeaderOverhead	8	Section 5.1
constantDataPayload	2	Section 5.1
tempThreshold	15.0	Section 3.5

Module NED file: **src/node/application/valueReporting/ValueReporting.ned**

Full hierarchy name: **SN.node[*].Application** *(shared)*

Parameter Name	**Default Value**	**Refer**
applicationID	“valueReporting”	Section 5.1
collectTraceInfo	false	Section 5.1
priority	1	Section 5.1
packetHeaderOverhead	8	Section 5.1
constantDataPayload	12	Section 5.1
maxSampleInterval	60000	below
minSampleInterval	1000	below
isSink	false	below

The max sample interval is used only to determine the effective sample interval of the app, the min sample interval is not currently used. The isSink parameter shows which node(s) is the sink.

Module NED file: **src/node/communication/CommunicationModule.ned**

Full hierarchy name: **SN.node[*].Communication**

Parameter Name	**Default Value**	**Refer**
MACProtocolName	"BypassMAC"	Section 3.2
RoutingProtocolName	“BypassRouting”	Section 3.2

Module NED file:

src/node/communication/mac/baselineBanMac/BaselineBANMac.ned

Full hierarchy name: **SN.node[*].Communication.MAC** *(shared)*

Parameter Name	**Default Value**	**Refer**
collectTraceInfo	false	Section 4

macMaxPacketSize	1000	Section 4.3.4
macBufferSize	32	Section 4.3.4
macPacketOverhead	7	Section 4.3.4
isHub	false	Section 4.3.4
allocationSlotLength	10	Section 4.3.4
beaconPeriodLength	32	Section 4.3.4
RAP1Length	8	Section 4.3.4
scheduledAccessLength	0	Section 4.3.4
scheduledAccessPeriod	1	Section 4.3.4
maxPacketTries	2	Section 4.3.4
contentionSlotLength	0.36	Section 4.3.4
enhanceGuardTime	false	Section 4.3.4
enhanceMoreData	false	Section 4.3.4
pollingEnabled	false	Section 4.3.4
naivePollingScheme	false	Section 4.3.4
pTIFS	0.03	Section 4.3.4
pTimeSleepToTX	0.2	Section 4.3.4
phyLayerOverhead	6	Section 4.3.4
phyDataRate		Section 4.3.4
mClockAccuracy	0.0001	Section 4.3.4

Module NED file: **src/node/communication/mac/bypassMac/BypassMAC.ned**

Full hierarchy name: **SN.node[*].Communication.MAC** *(shared)*

Parameter Name	**Default Value**	**Refer**
collectTraceInfo	false	Section 4
macMaxPacketSize	0	below
macPacketOverhead	8	below
macBufferSize	0	below

These four parameter are standard for all MACs. macMaxPacketSize defines a limit to the size of packets that the MAC can handle, macPacketOverhead gives you the overhead in bytes added to the Network(routing) packets received from the layer above, and macBufferSize is the size of the internal MAC buffer in packets.

Module NED file: **src/node/communication/mac/mac802154/Mac802154.ned**

Full hierarchy name: **SN.node[*].Communication.MAC** *(shared)*

Parameter Name	Default Value	Refer
collectTraceInfo	false	Section 4
printStateTransitions	false	Section 4.3.3
macMaxPacketSize	0	Section 4.3.3
macPacketOverhead	14	Section 4.3.3
macBufferSize	32	Section 4.3.3
enableSlottedCSMA	true	Section 4.3.3
enableCAP	true	Section 4.3.3
isFFD	false	Section 4.3.3
isPANCoordinator	false	Section 4.3.3
batteryLifeExtention	false	Section 4.3.3
frameOrder	4	Section 4.3.3
beaconOrder	6	Section 4.3.3
unitBackoffPeriod	20	Section 4.3.3
baseSlotDuration	60	Section 4.3.3
numSuperframeSlots	16	Section 4.3.3
macMinBE	5	Section 4.3.3
macMaxBE	7	Section 4.3.3
macMaxCSMABackoffs	4	Section 4.3.3
macMaxFrameRetries	2	Section 4.3.3
maxLostBeacons	4	Section 4.3.3
minCAPLength	440	Section 4.3.3
requestGTS	0	Section 4.3.3
phyDelayForValidCS	0.128	Section 4.3.3
phyDataRate		Section 4.3.3
phyDelayRx2Tx	0.02	Section 4.3.3
phyFrameOverhead	6	Section 4.3.3
phyBitsPerSymbol		Section 4.3.3
guardTime	1	Section 4.3.3

Module NED file: **src/node/communication/mac/tMac/TMAC.ned**

Full hierarchy name: **SN.node[*].Communication.MAC** *(shared)*

Parameter Name	Default Value	Refer
collectTraceInfo	false	Section 4

printStateTransitions	false	Section 4.3.2
ackPacketSize	11	Section 4.3.2
syncPacketSize	11	Section 4.3.2
rtsPacketSize	13	Section 4.3.2
ctsPacketSize	13	Section 4.3.2
macMaxPacketSize	0	Section 4.3.2
macPacketOverhead	11	Section 4.3.2
macBufferSize	32	Section 4.3.2
maxTxRetries	2	Section 4.3.2
allowSinkSync	true	Section 4.3.2
useFrts	false	Section 4.3.2
useRtsCts	true	Section 4.3.2
disableTAextension	false	Section 4.3.2
conservativeTA	true	Section 4.3.2
resyncTime	6	Section 4.3.2
contentionPeriod	10	Section 4.3.2
listenTimeout	15	Section 4.3.2
waitTimeout	5	Section 4.3.2
frameTime	610	Section 4.3.2
collisionResolution	0	Section 4.3.2
phyDelayForValidCS	0.128	Section 4.3.2
phyDataRate	250	Section 4.3.2
phyFrameOverhead	6	Section 4.3.2

Module NED file: **src/node/communication/mac/tunableMac/tunableMAC.ned**

Full hierarchy name: **SN.node[*].Communication.MAC** *(shared)*

Parameter Name	**Default Value**	**Refer**
collectTraceInfo	false	Section 4
printStateTransitions	false	
dutyCycle	1.0	Section 4.3.1
listenInterval	10	Section 4.3.1
beaconIntervalFraction	1.0	Section 4.3.1
probTx	1.0	Section 4.3.1
numTx	1	Section 4.3.1
randomTxOffset	0.0	Section 4.3.1

reTxInterval	0.0	Section 4.3.1
backoffType	1	Section 4.3.1
backoffBaseValue	16	Section 4.3.1
CSMApersistance	0	Section 4.3.1
txAllPacketsInFreeChannel	true	Section 4.3.1
sleepDuringBackoff	false	Section 4.3.1
macMaxPacketSize	0	Section 4.3.1
macPacketOverhead	9	Section 4.3.1
beaconFrameSize	14	Section 4.3.1
macBufferSize	32	Section 4.3.1
phyDataRate	250.0	Section 4.3.1
phyDelayForValidCS	0.128	Section 4.3.1
phyFrameOverhead	6	Section 4.3.1

Module NED file: **src/node/communication/radio/Radio.ned**

Full hierarchy name: **SN.node[*].Communication.Radio** *(shared)*

Parameter Name	**Default Value**	**Refer**
collectTraceInfo	false	Section 4
RadioParametersFile	“”	Section 4.2.1
mode	“”	Section 4.2.2
state	“RX”	Section 4.2.2
TxOutputPower	“”	Section 4.2.2
sleepLevel	“”	Section 4.2.2
carrierFreq	2400.0	Section 4.2.2
collisionModel	2	Section 4.2.2
CCAthreshold	-95.0	Section 4.2.2
symbolsForRSSI	8	Section 4.2.2
carrierSenseInterruptEnabled	false	Section 4.2.2
bufferSize	16	Section 4.2.2
maxPhyFrameSize	1024	below
phyFrameOverhead	6	below

maxPhyFrameSize specifies the maximum length of a packet the radio can handle in bytes. Some radios do pose restrictions on the size of packets they can handle so this parameter can be useful modelling this behaviour. If set to 0 or less, it means we have no limit.

phyFrameOverhead specifies the overhead in bytes added to a packet received by the MAC before being transmitted to the channel.

Module NED file:

src/node/communication/routing/bypassRouting/BypassRouting.ned

Full hierarchy name: **SN.node[*].Communication.Routing** *(shared)*

Parameter Name	Default Value	Refer
collectTraceInfo	false	Section 4
maxNetFrameSize	0	Section 4.4
netDataFrameOverhead	10	Section 4.4
netBufferSize	32	Section 4.4

Module NED file:

src/node/communication/routing/multipathRingsRouting/MultipathRingsRouting.ned

Full hierarchy name: **SN.node[*].Communication.Routing** *(shared)*

Parameter Name	Default Value	Refer
collectTraceInfo	false	Section 4
maxNetFrameSize	0	Section 4.4
netBufferSize	32	Section 4.4
netDataFrameOverhead	14	Section 4.4
mpathRingsSetupFrameOverhead	13	Section 4.4
netSetupTimeout	50	Section 4.4

Module NED file: **src/node/mobilityManager/LineMobilityManager.ned**

Full hierarchy name: **SN.node[*].MobilityManager** *(shared)*

Parameter Name	Default Value	Refer
collectTraceInfo	false	Section 4
updateInterval	1000	Section 4.7
xCoorDestination	0	Section 4.7
yCoorDestination	0	Section 4.7
zCoorDestination	0	Section 4.7
speed	1	Section 4.7

Module NED file: **src/node/mobilityManager/NoMobilityManager.ned**

Full hierarchy name: **SN.node[*].MobilityManager** *(shared)*

Parameter Name	Default Value	Refer
collectTraceInfo	false	Section 4

Module NED file: **src/node/resourceManager/ResourceManager.ned**

Full hierarchy name: **SN.node[*].ResourceManager**

Parameter Name	Default Value	Refer
collectTraceInfo	false	Section 4
ramSize	0	Section 4.8
flashSize	0	Section 4.8
flashWriteCost	0	Section 4.8
flashReadCost	0	Section 4.8
imageSize	0	Section 4.8
cpuPowerSpeedLevelNames	“”	Section 4.8
cpuPowerPerLevel	“”	Section 4.8
cpuSpeedPerLevel	“”	Section 4.8
cpuInitialPowerLevel	-1	Section 4.8
sigmaCPUClockDrift	0. 00003	Section 4.8
initialEnergy	18720	Section 4.8
baselineNodePower	6	Section 4.8
periodicEnergyCalculationInterval	1000	Section 4.8

Module NED file: **src/node/sensorManager/SensorManager.ned**

Full hierarchy name: **SN.node[*].SensorManager**

Parameter Name	Default Value	Refer
collectTraceInfo	false	Section 4
numSensingDevices	1	Section 4.6
pwrConsumptionPerDevice	“0.02”	Section 4.6
sensorTypes	“Temperature”	Section 4.6
corrPhyProcess	“0”	Section 4.6
maxSampleRates	“1”	Section 4.6
devicesBias	“0.1”	Section 4.6

devicesDrift	“”	Section 4.6
devicesNoise	“0.1”	Section 4.6
devicesHysterisis	“”	Section 4.6
devicesSensitivity	“0”	Section 4.6
devicesResolution	"0.001"	Section 4.6
devicesSaturation	“1000”	Section 4.6

Module NED file:

src/physicalProcess/carsPhysicalProcess/CarsPhysicalProcess.ned

Full hierarchy name: **SN.physicalProcess[*]** *(shared)*

Parameter Name	**Default Value**	**Refer**
collectTraceInfo	false	Section 4
max_num_cars	5	Section 4.5.2
car_speed	16.0	Section 4.5.2
car_value	30.0	Section 4.5.2
car_interarrival	20	Section 4.5.2
point1_x_coord		Section 4.5.2
point2_x_coord		Section 4.5.2
point1_y_coord		Section 4.5.2
point2_y_coord		Section 4.5.2
description	“Moving cars”	Section 4.5.2

Module NED file:

src/physicalProcess/customizablePhysicalProcess/ CustomizablePhysicalProcess.ned

Full hierarchy name: **SN.physicalProcess[*]** *(shared)*

Parameter Name	**Default Value**	**Refer**
collectTraceInfo	false	Section 4
inputType	1	Section 4.5.1
directNodeValueAssignment	"(0)"	Section 4.5.1
multiplicative_k	0.25	Section 4.5.1
attenuation_exp_a	1.0	Section 4.5.1

sigma	0.2	Section 4.5.1
max_num_snapshots	10	Section 4.5.1
numSources	1	Section 4.5.1
source_0	"0 10 10 30.5; 5 10 10 45; 12 10 10 7.3"	Section 4.5.1
source_1	“”	Section 4.5.1
source_2	“”	Section 4.5.1
source_3	“”	Section 4.5.1
source_4	“”	Section 4.5.1
tracefileName	“”	Section 4.5.1
description	“Fire”	Section 4.5.1

Module NED file: **src/wirelessChannel/WirelessChannel.ned**

Full hierarchy name: **SN.wirelessChannel**

Parameter Name	**Default Value**	**Refer**
collectTraceInfo	false	Section 4
onlyStaticNodes	true	Section 4.1.2
xCellSize	5	Section 4.1.2
yCellSize	5	Section 4.1.2
zCellSize	1	Section 4.1.2
pathLossExponent	2.4	Section 4.1.1
PLd0	55	Section 4.1.1
d0	1.0	Section 4.1.1
sigma	4.0	Section 4.1.1
bidirectionalSigma	1.0	Section 4.1.1
pathLossMapFile	“”	Section 4.1.1
temporalModelParametersFile	“”	Section 4.1.3
signalDeliveryThreshold	-100	Section 4.1.4

7 References

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