Underwater Networks Handbook

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Preface

What is this book about?

About 71% of Earth's surface is covered with water, and about 97% of the water is in our oceans. Although the ocean plays a critical role in everything from the air we breathe to daily weather and climate patterns, we know very little about it. To really understand our oceans, we need a way to sense and observe the numerous complex processes that drive the ocean environment, and to report the data collected back to our data centers. While cabled ocean observatories have been established in a few locations, they are too expensive to setup and maintain for large scale data collection across the vast oceans.

Over the past few decades, wireless communication technology has percolated into every aspect of our lives, and we have come to take it for granted. This technology forms the bedrock of wireless sensor networks, allowing us to gather data with ease. Most of the wireless communication technology we use relies on electromagnetic waves (e.g. radio waves, visible light) that get rapidly absorbed by water. Hence the technology is ineffective for underwater communication, except at very short distances or extremely low data rates. Most underwater communication systems today use acoustic waves, which can travel long distances in the right conditions. At short distances in clear waters, optical communication systems are sometimes used for high speed communications. Although these communication technologies can be leveraged to establish point-to-point communication links, these links do not integrate well with networking technology available today.

The **Unet project** strives to develop technologies that allow us to build communication networks that extend underwater, be it via acoustic, optical, or even wired links. Some nodes in such networks may be above water, while others are underwater. In this handbook, we explore how to build such networks using **UnetStack3**, an agent-based network technology that was developed in the Unet project.

Who should read this book?

This book is intended for readers interested in deploying networks that extend underwater, or developing technology or protocols for use in underwater networks. Part I of the book provides an overview, and is recommended for all readers. Part II is aimed at readers who wish to deploy and maintain networks that extend underwater. Part III is aimed at application developers and software engineers who wish to integrate with UnetStack-based networks. Parts IV and V dive deeper into UnetStack, and are intended for researchers and engineers who wish to develop, simulate and test novel underwater networking protocols.

The book assumes that readers have a basic understanding of traditional networking technology. While expert software development skills are not required to benefit from this book, familiarity with scripting or programming is essential. Readers with knowledge of Java, Groovy and/or Python will find it easy to follow the examples in the text, but even readers without prior knowledge of these languages should be able to pick up necessary skills along the way.

Part I: Introduction to UnetStack

Chapter 1. Introduction

1.1. What is a Unet?

The Internet has changed our lives beyond anyone's wildest expectations, fundamentally changing the way we interact, the way we learn, and the way we work. More recently, devices have started connecting to the Internet, and communicating with other devices. This *Internet of Things* (IoT) has the potential to have a huge impact on the way we understand our environment, and interact with it. Given that most of our planet's surface is covered with water, would it then not make sense that at least some of these devices might be in water? Some devices might measure ocean temperature and acidification to give us a handle on climate change, while other devices might monitor fresh water quality to ensure safe drinking water for us. Autonomous underwater vehicles (AUVs) may patrol our coastal waters looking for intruders, or tracking down sources of pollution or nutients that encourage harmful algal blooms. Be it static sensors or mobile AUVs, we need a way to connect them into a network that we can communicate and interact with. The *Unet project* strives to develop technologies that allow us to do precisely this. In this handbook, we explore how to use UnetStack3, a technology developed as part of the Unet project, to build communication networks that extend underwater.

Most wireless technologies today rely on electromagnetic waves that don't propagate well underwater. Therefore, to extend IoT underwater, we typically need a mix of technologies — cabled links where possible, otherwise radio frequency (RF) wireless links above water, and mid-to-long range wireless acoustic or short-range wireless optical links underwater. A "Unet" network (which we will simply call *Unet* henceforth) consists of several nodes (underwater, on the surface of water, or above water) that communicate over various types of links, as shown in Figure 1.

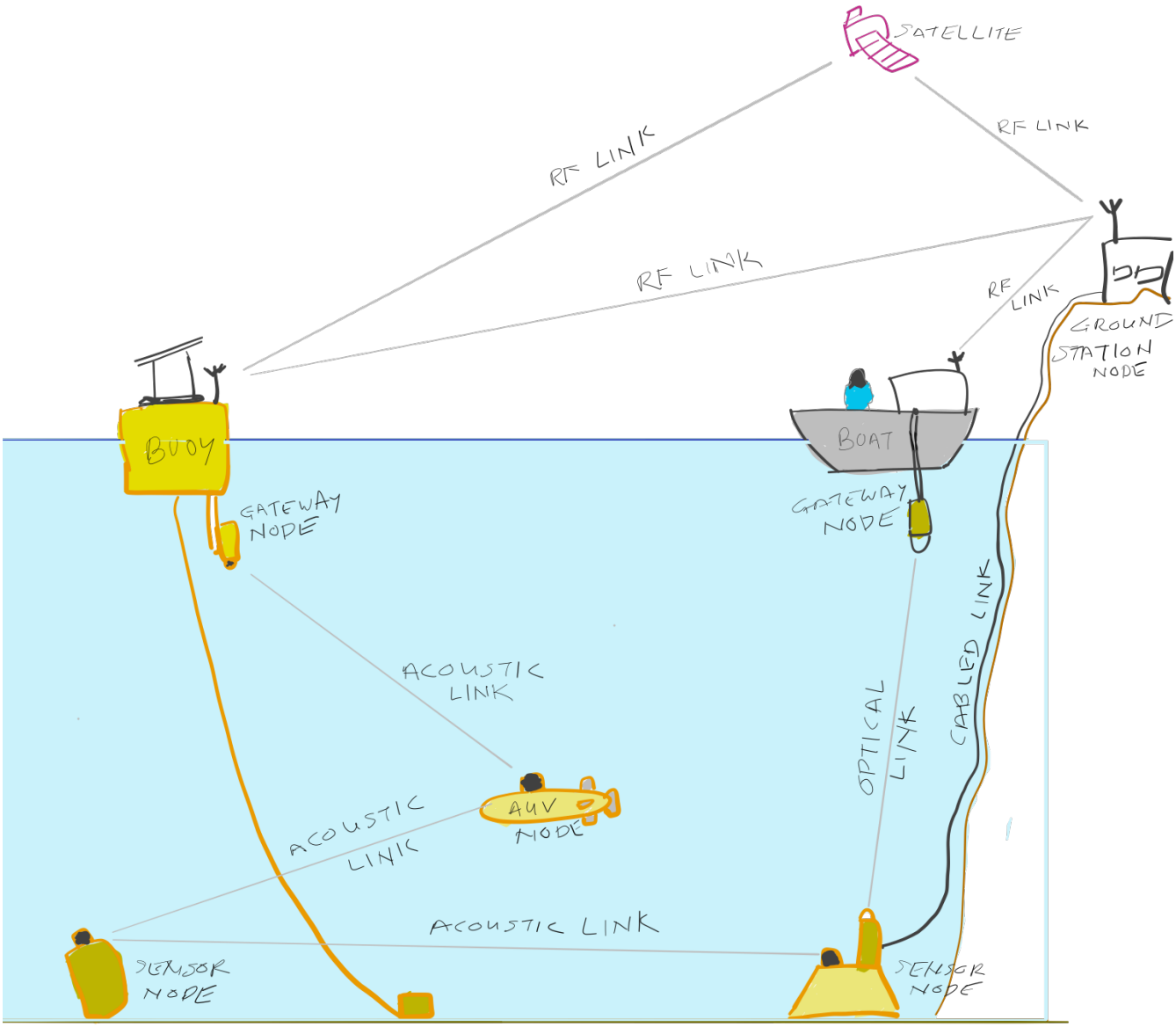


Figure 1. A typical Unet consists of static and mobile nodes, both underwater and in air, with bidirectional acoustic, optical, electromagnetic and cabled links connecting pairs of nodes.

A Unet consists of many *Unet nodes* (e.g. underwater sensor nodes, Autonomous Underwater Vehicles (AUVs), gateway buoys, ground stations, boats/ships) that generate, consume or relay data over a variety of links:

- **Acoustic links** are typically used for mid-to-long range communication underwater. These links usually offer low data rates and long propagation delay due to the slow speed of sound in water (as compared to EM waves).
- **Optical links** are used for short range high data rate communications in water.
- **RF links** are used for mid range communication in air.
- **GSM links** are used for near-shore connectivity through air.
- **Satellite links** are used for nodes that are far out at sea, and cannot be reached through GSM or RF links. These links usually are expensive and offer relatively low data rates.
- **Wired links** (Ethernet, serial, fiber optic) are used for long-term static deployments underwater, or over short distances where cabling is feasible.

- In some cases, nodes are retreived and data is transferred from them to other nodes in the network on a regular basis, using physical media (e.g. USB drives, SD cards, etc). These links usually offer very high data rates, but are only available intermittently. We dub such links as **Sneakernet links**.

A link is simply a logical connection between two nodes, often provided by equipping both the nodes with modems. We summarize various types of links in Table 1.

Table 1. Various types of links in a typical Unet, and their characteristics.

Link type	Communication range[#]	Data rate[#]	Latency
High-frequency acoustic (underwater)	Short	Medium	milliseconds
Mid-frequency acoustic (underwater)	Medium	Low	seconds
Low-frequency acoustic (underwater)	Long	Very low	seconds
Optical (underwater)	Very short	High	Negligible
RF (in air)	Medium	Medium	Negligible
GSM (in air, near shore)	Medium	Medium	milliseconds
Satellite (in air)	Long	Low	milliseconds
Wired/cabled	Long (expensive)	High	Negligible
Sneakernet	Long (intermittent)	Very high	hours or days

[#]Communication range and data rate vary substantially across devices and environments. Short range usually is in tens of meters, medium range is several km, and long range is typically tens of km. Low data rates are in hundreds of bps, medium data rates are in kbps, and high data rates are in Mbps.

1.2. UnetStack

Unet nodes are equipped with one or more network interfaces that allow communication over some of these links. For example, to communicate over an underwater acoustic link, we need an *underwater acoustic modem*. For an underwater optical link, we use an *underwater optical modem*. Most RF, GSM, satellite or wired links would be accessed over a standard TCP/IP network interface. In all cases, each Unet node would run the *UnetStack* software that allows us to effectively communicate over all of these types of links using a common Application Programming Interface (API). UnetStack API bindings are available for several languages including Java, Groovy, Python, Julia, C, Javascript, etc.

UnetStack has a several components, as depicted in Figure 2:

- The **Unet framework** provides core services, messages, agents and APIs needed by UnetStack.
- The **Unet basic stack** is a collection of agents providing services and functionality required by typical Unets. These agents, together with the Unet framework, are sufficient to build fully functional Unets.
- The **Unet premium stack** is a collection of agents providing advanced functionality and/or higher performance. Many of the premium agents provide similar services as the basic ones, but used advanced techniques for better performance and bandwidth efficiency.
- The **Unet simulator** is able to simulate Unets with many nodes on a single computer. It can run in

realtime simulation mode for interactive testing of agents and protocols, working to provide the user with the same user experience as in a real Unet. It can also be run in *discrete event simulation mode* to perform a large number of simulations in a short time, allowing Monte Carlo testing and performance evaluation of network protocols.

- The **Unet IDE** is an integrated development environment (IDE) for developers to develop, simulate and test Unet agents and protocols. It also enables the developer to visualize and interact with simulated networks.
- **Unet audio** is a sound card based realtime software defined open architecture acoustic modem (SDOAM) that runs on desktop, laptop or single-board computers, and can be used to build and test simple Unets. It is a great tool for not only developing and testing network protocols, but also developing acoustic communication techniques.

The components are packaged into various editions. The **community edition** is downloadable free of charge for educational and research purposes. It has all the components required to develop, simulate, test and deploy Unets. The commercial and OEM editions package offer advanced functionality, better performance and tighter integration with vendor-specific hardware.

Figure 2. An overview of UnetStack components.

In the next few chapters, we will learn how to use UnetStack and how to customize it to meet our networking needs. In some cases, it may be necessary to prototype and simulate a Unet before it is actually implemented. We will also learn how to do that using the Unet simulator.

Chapter 2. Getting started

In this chapter, you will learn how to set up a simple 2-node underwater network with an acoustic link. If you already own a couple of UnetStack-compatible acoustic modems, you can certainly use them! And we'll show you how to do that in Section 2.6. But let us first start with a simulated 2-node underwater network, since all you need for this is a computer and the Unet simulator.

2.1. Setting up a simple simulated network

Download UnetStack community edition for your OS and untar/unzip it. Open a terminal window in the simulator's root folder and start the simulator:

```
$ bin/unet samples/2-node-network.groovy

2-node network
--------------

Node A: tcp://localhost:1101, http://localhost:8081/
Node B: tcp://localhost:1102, http://localhost:8082/
```

If you're using Windows, you may need to use:
`bin\unet samples\handbook\2-node-network.groovy`

Open two web browser windows and key in the two http URLs shown above in each browser. This should give you a command shell for node A and node B in the two browser windows.

2.2. Making your first transmission

On the command shell for node A, type:

```
> tell 0, 'hello!'
AGREE
```

Address 0 is a broadcast address, so you did not need to explicitly know the address of node B to transmit a message to it. After a short delay, you should see the message on the command shell for node B:

```
[232]: hello!
```

Congratulations!!! You have successfully transmitted your first message over the Unet.

The `[232]` that you see on node B is the *from* address (of node A). The simulator automatically allocates addresses to each node. You can easily find out the addresses of both nodes (on either node):

```
> host('A')
232
> host('B')
31
```

You can try sending a message back from node B:

```
> tell 232, 'hi!'
```

and you should see the message `[31]: hi!` on node A after just a short delay.

You could have specified the hostname instead of the address when sending the message:
`tell host('A'), 'hi!'`.

2.3. Propagation delay & ranging

In the simulation, nodes A and B are placed 1 km apart. Since the speed of sound in water is about 1500 m/s (exact sound speed depends on temperature, salinity and depth), the signals take about 0.7 s to travel between the simulated nodes. This explains the short delays you see between sending the message from one node and receiving it on the other. You can also make use of this time delay to measure the distance between the nodes!

On node A, type:

```
> range host('B')
999.7
```

You got an estimate of 999.7 m for the range between the two nodes.

2.4. Sending & receiving application data

In real applications, you may want to send complex *datagrams* (messages) programmatically between nodes. The simplest way to do this is via the *UnetSocket* API (Chapter 9). Let's try it!

On node B, type:

```
> s = new UnetSocket(this);            ①
> rx = s.receive()                     ②
```

① Open a socket on node B (`this` refers to node B, since you are typing this on node B's command shell). The semicolon (";") at the end of the statement simply prevents the shell from printing the return value automatically.

② Receive a datagram. This call blocks until a datagram is available.

On node A, type:

```
> s = new UnetSocket(this);
> s.send('hello!' as byte[], 0)          ①
true
> s.close()
```

① Send 6 ASCII bytes ('hello!') to address 0 (broadcast address). The `as byte[]` is necessary in Groovy to convert the string you specified into a byte array that the `send()` method expects.

Node B will receive the bytes as a `RxFrameNtf` message. You can check the data in the received datagram on the command shell for node B, and close the socket:

```
RxFrameNtf:INFORM[type:DATA from:232 rxTime:4134355059 (6 bytes)]
> rx.data
[104, 101, 108, 108, 111, 33]           ①
> new String(rx.data)                   ②
hello!
> s.close()
```

① These are the bytes representing the ASCII characters ['h', 'e', 'l', 'l', 'o', '!'].

② This puts together the ASCII characters in the byte array into a String.

While we demonstrated the use of the `UnetSocket` API in Groovy on the command shell, the same commands work in a Groovy script or application, with one minor modification. When the socket is opened, you will have to specify the connection details (such as host name or IP address, and the API port number) of the modem (or simulated modem) to connect to. For example, if UnetStack is running on `localhost` at port number 1101, you can connect to it using: `s = new UnetSocket('localhost', 1101);`

2.5. Sending & receiving from a Python application

UnetStack provides API bindings for many languages (Java, Groovy, Python, Julia, C, Javascript, etc). We demonstrate the use of the Python API here, but the usage is quite similar in other languages too.

We'll assume you have Python 3.x already installed. Let us start by installing the UnetStack Python API bindings:

```
$ pip install unetpy
Collecting unetpy
  Using cached
https://files.pythonhosted.org/packages/eb/f1/0efa3cff9c25322169041d3d804691ad24ccd732d6e284e209d20a89336f
/unetpy-3.0.2-py3-none-any.whl
Collecting fjagepy>=1.6 (from unetpy)
  Using cached
https://files.pythonhosted.org/packages/3d/38/159338ad451218652aec30ebd9513d6e26ea4679903c47df10def1457652
/fjagepy-1.6-py3-none-any.whl
Requirement already satisfied: numpy>=1.11 in /Users/anjangi/Documents/python-env/publish-
env/lib/python3.7/site-packages (from unetpy) (1.17.2)
Installing collected packages: fjagepy, unetpy
Successfully installed fjagepy-1.6 unetpy-3.0.2
```

We will now write `tx.py` and `rx.py` scripts to transmit and receive a datagram respectively. We assume

that you have the two-node network setup from the previous section with node A and B available on `localhost` API port 1101 and 1102 respectively.

`tx.py`

```
from unetpy import UnetSocket

s = UnetSocket('localhost', 1101)               ①
s.send('hello!', 0)                             ②
s.close()
```

① Connect to node A (`localhost` API port 1101).

② Broadcast a 6-byte datagram. Address 0 is the broadcast address.

`rx.py`

```
from unetpy import UnetSocket

s = UnetSocket('localhost', 1102)               ①
rx = s.receive()                                ②
print('from node', rx.from_, ':', str(rx.data))  ③
s.close()
```

① Connect to node B (`localhost` API port 1102). Change the `localhost` to modem B's IP address and port 1102 to port 1100, if you are working with a modem.

② Blocking `receive()` will only return when a datagram is received or the socket is closed. If a datagram is received, `rx` will contain the notification message with the details of the datagram.

③ In Python `from` is a keyword and cannot be used as an field name. We therefore use `from_` for the source node address.

First run `python rx.py` to start reception. Then, on a separate terminal window, run `python tx.py` to initiate transmission. You should see the received datagram printed by the `rx.py` script:

```
$ python rx.py
from node 1 : Hello!
```

Once you are done with your testing, it is time to shutdown the simulation. You can do that by pressing `Ctrl-C` on the terminal where you started the simulator. Alternatively, you can go to the shell of one of the nodes, and type: `shutdown`.

2.6. Using acoustic modems

So far, we have worked with a simulator. While the experience is similar, it is not exactly the same. There is no real substitute for working with real modems. If you happen to have two UnetStack-compatible acoustic modems, you can use them to set up a simple 2-node network. Put them in a water body (tank, bucket, lake, sea, ...), power them on, and connect each to a computer over Ethernet. The setup would look something like this:

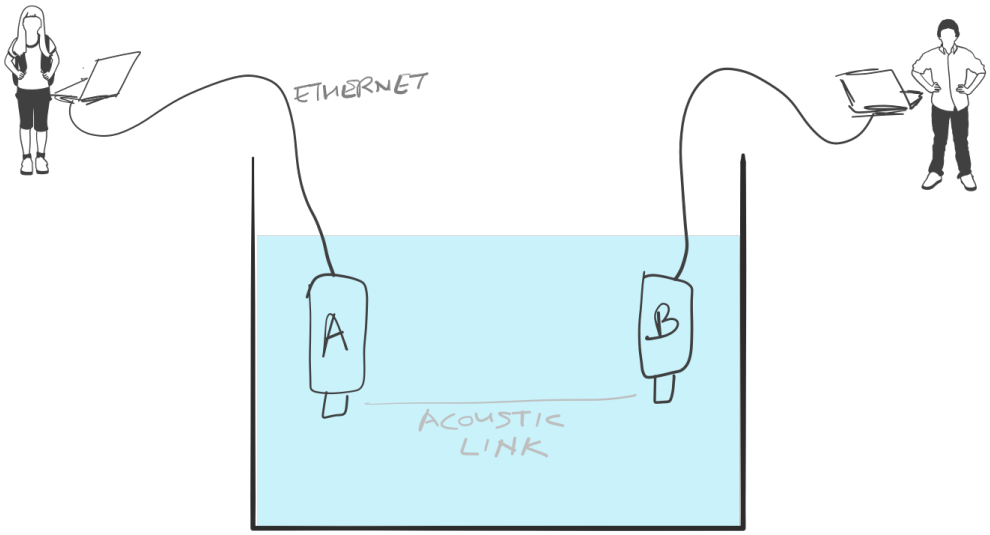


Figure 3. Two-node acoustic underwater network

On each computer, open a web browser and key in the IP address of the respective modem. This should give us a command shell for node A and node B on the two computers.

If you only have one computer available, you can connect both modems to the same Ethernet switch and connect to each modem's IP address in separate browser windows.

When working with modems, you may need to adjust the transmit power level to a suitable level for use in the water body that you have the modems in. Too high or too low a power level will not allow the modems to communicate well. The modem transmit power can be adjusted using the `plvl` command. Type `help plvl` on the command shell for node A to see examples of how the command is used:

```
> help plvl
plvl - get/set TX power level for all PHY channel types

Examples:
  plvl                      // get all power levels
  plvl -10                  // set all power to -10 dB
  plvl(-10)                 // alternative syntax
  plvl = -10                // alternative syntax
```

The `help` command is your friend! Just type `help` to see a list of help topics. Type `help` followed by a command name, topic or parameter (you'll learn more about these later) to get help information.

Assuming you have the modems in a bucket, you'll need a fairly low transmit power. On node A, let us set the transmit power to -50 dB and try a transmission:

```
> plvl -50
OK
> tell 0, 'hello!'
AGREE
```

If all goes well, you should see the message on node B:

```
[232]: hello!
```

Of course you'll see a different "from" address than the one shown in the example here. It will be the actual address of your modem A. In case you don't see the message on node B after a few seconds, you may want to adjust the power level up or down and try again.

All the other examples shown earlier in this chapter will also work with the modems. You'll just need to replace the `localhost` with the appropriate modem IP address, and the API port for the modem will usually be 1100.

2.7. Transmitting and recording arbitrary acoustic waveforms

If you have UnetStack-compatible acoustic modems that support the BASEBAND service, you can use them to transmit and record arbitrary acoustic signals. Even without access to modems, you can try this out using the Unet audio SDOAM — a fully functional modem that uses your computer's soundcard for transmission and reception. To start Unet audio, open a terminal window in the simulator's root folder and type:

```
$ bin/unet audio
Modem web: http://localhost:8080/
```

This should start up the SDOAM and open a browser with a command shell accessing the modem. If the browser does not automatically open, just enter the modem web URL shown above in your browser. At the command shell, you can try transmitting a message:

```
> tell 0, 'hello!'
AGREE
```

You should hear the transmission from your computer speaker! If you don't, check your speaker volume and try again.

If you have 2 computers running the unet audio SDOAM, you can receive the transmitted signal on the second computer and see the received message: `[1]: hello!`.

Next, try sending a simple 10 kHz tonal signal:

```
> bbtx cw(10000, 0.5)                    ①
AGREE
phy >> TxFrameNtf:INFORM[txTime:4104441] ②
```

① Request transmission of a continuous wave (cw) signal of 10 kHz and 0.5 seconds duration.

② Notification that the signal was successfully transmitted.

You should hear a 0.5 second 10 kHz tone from your computer speaker. The `bbtx` command requests transmission of a baseband signal. The function `cw()` generates such a signal based on the specified

frequency and duration.

To generate the baseband representation of the signal you wish to transmit, you will need to know the carrier frequency and the baseband sampling rate of the modem:

```
> phy.basebandRate
12000.0
> phy.carrierFrequency
12000.0
```

For the unet audio SDOAM, the carrier frequency is 12 kHz and the baseband sampling rate is 12 kSa/s.

The baseband signal is represented as a floating point array with alternate real and imaginary components in Java/Groovy. For languages that support complex numbers (e.g. Python, Julia), the signal is simply an array of complex numbers.

You can equally easily ask the SDOAM to make an acoustic recording for you:

```
> bbrec 12000                              ①
AGREE
phy >> RxBasebandSignalNtf:INFORM[adc:1 rxTime:1911353 rssi:-61.2 fc:12000.0 fs:12000.0 (12000 baseband
samples)]
```

① Request recording of 12000 baseband samples (1 second duration).

The recording is sent to you as a `RxBasebandSignalNtf` message with 12000 baseband samples in the `signal` field. You can check the first 32 samples:

```
> ntf.signal[0..31]
[-3.735939E-4, 6.7323225E-4, 7.94507E-4, 5.0331384E-4, 0.0012656008, -0.0010853912, -2.0923217E-4,
-8.322359E-4, 1.5215082E-4, 2.417963E-4, -3.0220395E-5, -5.190366E-4, -6.904016E-4, -7.3395047E-4,
3.9846844E-5, 5.161132E-4, 0.0013477469, 6.2060537E-4, 1.00925405E-4, -3.974573E-4, -8.8431453E-4,
-5.807383E-4, -5.730035E-4, -8.5867435E-4, -9.026667E-4, 2.2320295E-5, -1.7575005E-5, 0.0010946163,
7.7881676E-4, -3.7582265E-4, -9.449492E-4, -1.7722705E-4]
```

The values you'd see would natually be different, since the SDOAM would have recorded whatever sounds it heard using your computer's microphone.

While we illustrated the use of the BASEBAND service using the `bbtx` and `bbrec` commands, the same functionality can be accessed using the `TxBasebandSignalReq` and the `RecordBasebandSignalReq` messages. This is useful if you want to access the functionality from an agent or through the external gateway API (e.g. from a Jupyter Python notebook). You will learn how to do this in Chapter 15.

Chapter 3. UnetStack basics

UnetStack is an *agent-based network stack*. Each *agent* is similar to a *layer* in a traditional network stack, but has more flexibility to use the scarce resources (bandwidth, energy, etc) in the Unet more efficiently. In order to develop Unet applications, we need to understand some basic concepts in UnetStack.

3.1. The command shell

The simplest way to interact with UnetStack is via the command shell (or simply *shell*). The shell may be accessed on the console, a TCP/IP port or via the web interface. In Chapter 2, we have already seen how to set up a 2-node network and access the command shell for each of the nodes using a web browser. For the rest of this section, we assume that you have shells open on nodes A and B.

On node A, we can ask for a list of agents running:

```
> ps
remote: org.arl.unet.remote.RemoteControl - IDLE
state: org.arl.unet.state.StateManager - IDLE
rdp: org.arl.unet.net.RouteDiscoveryProtocol - IDLE
ranging: org.arl.unet.phy.Ranging - IDLE
uwlink: org.arl.unet.link.ReliableLink - IDLE
node: org.arl.unet.nodeinfo.NodeInfo - IDLE
websh: org.arl.fjage.shell.ShellAgent - RUNNING
simulator: org.arl.unet.sim.SimulationAgent - IDLE
phy: org.arl.unet.sim.HalfDuplexModem - IDLE
bbmon: org.arl.unet.bb.BasebandSignalMonitor - IDLE
arp: org.arl.unet.addr.AddressResolution - IDLE
transport: org.arl.unet.transport.SWTransport - IDLE
router: org.arl.unet.net.Router - IDLE
mac: org.arl.unet.mac.CSMA - IDLE
```

We can further ask for more details of a specific agent:

```
> phy
<<< HalfDuplexModem >>>

[org.arl.unet.DatagramParam]
  MTU = 56

[org.arl.unet.bb.BasebandParam]
  basebandRate = 12000.0
  carrierFrequency = 12000.0
  maxPreambleID = 4
  maxSignalLength = 65536
  preambleDuration = 0.2
  signalPowerLevel = -10.0

[org.arl.unet.phy.PhysicalParam]
  busy = false
  maxPowerLevel = 0.0
  minPowerLevel = -96.0
  propagationSpeed = 1534.4574
  refPowerLevel = 185.0
  rxEnable = true
  rxSensitivity = -200.0
  time = 3283592429
  timestampedTxDelay = 1.0

[org.arl.unet.sim.HalfDuplexModemParam]
  basebandRxDuration = 1.0
  clockOffset = 3248.3442
```

We asked for details of the agent phy, and we got a list of parameters supported by the agent. We can get or set individual parameters of the agent:

```
> phy.MTU
56
> phy.rxEnable
true
> phy.rxEnable = false
false
> phy.rxEnable
false
> phy.rxEnable = true
true
```

To find out more about a specific parameter, we can ask for help on the parameter:

```
> help phy.MTU
phy.MTU - maximum transmission unit (MTU) in bytes
> help phy.rxEnable
phy.rxEnable - true if reception enabled
```

We can also ask for help on an agent:

```
> help phy
phy - access to physical service

Examples:
  phy                           // access physical parameters
  phy[CONTROL]                  // access control channel parameters
  phy[DATA]                     // access data channel parameters
  phy << msg                    // send request msg to physical agent
  phy.rxEnable = false          // disable reception of frames

Commands:

- plvl - get/set TX power level for all PHY channel types

Parameters:

The following parameters are available on all modems. Additional modem
dependent parameters are also available. For information on these
parameters type "help modem".

- phy.MTU - maximum transmission unit (MTU) in bytes
- phy.rxEnable - true if reception enabled
- phy.propagationSpeed - propagation speed in m/s
- phy.timestampedTxDelay - delay before TX of timestamped frames
- phy.time - physical layer time (us)
- phy.busy - true if modem is TX/RX a frame, false if idle
- phy.refPowerLevel - reference power level in dB re uPa @ 1m
- phy.maxPowerLevel - maximum supported power level (relative to reference)
- phy.minPowerLevel - minimum supported power level (relative to reference)

Channel Parameters:

The following parameters are available on all modems. Additional modem
dependent parameters are also available. For information on these
parameters type "help modem".

- phy[].MTU - maximum transmission unit (MTU) in bytes
- phy[].dataRate - effective frame data rate (bps)
- phy[].frameDuration - frame duration (seconds)
- phy[].powerLevel - powel level used for transmission (relative to reference)
- phy[].errorDetection - number of bytes for error detection
- phy[].frameLength - frame length (bytes)
- phy[].maxFrameLength - maximum settable frame length (bytes)
- phy[].fec - forward error correction code
- phy[].fecList - list of available forward error correction codes
```

From this help, we see that phy agent also supports channel parameters (also known as *indexed* parameters). It supports two logical channels, CONTROL (1) and DATA (2). The CONTROL channel is meant for low-rate robust data transmission, whereas the DATA channel is typically configured for higher rate data transmission. Channel parameters work in the same way as normal parameters, but with an index:

```
> phy[CONTROL]
<<< PHY >>>

[org.arl.unet.DatagramParam]
  MTU = 16

[org.arl.unet.phy.PhysicalChannelParam]
  dataRate = 256.0
  errorDetection = 1
  fec = 0
  fecList = null
  frameDuration = 0.95
  frameLength = 24
  janus = false
  llr = false
  maxFrameLength = 128
  powerLevel = -10.0

> phy[DATA]
<<< PHY >>>

[org.arl.unet.DatagramParam]
  MTU = 56

[org.arl.unet.phy.PhysicalChannelParam]
  dataRate = 1024.0
  errorDetection = 1
  fec = 0
  fecList = null
  frameDuration = 0.7
  frameLength = 64
  janus = false
  llr = false
  maxFrameLength = 512
  powerLevel = -10.0

> phy[CONTROL].MTU
16
> phy[CONTROL].frameLength = 32
32
> phy[CONTROL].frameLength
32
> phy[CONTROL].MTU
24
> phy[CONTROL].frameLength = 24
24
```

The actual parameters you see may differ if you are working with a modem, depending on the specific capabilities of the modem. Use `help` to find out more about any listed parameter on your modem, or refer to the modem's documentation for further information.

Most agents also support some commands. For example, the `phy` agent supports the `plvl` command:

```
> help plvl
plvl - get/set TX power level for all PHY channel types

Examples:
  plvl                      // get all power levels
  plvl -10                  // set all power to -10 dB
  plvl(-10)                 // alternative syntax
  plvl = -10                // alternative syntax

> plvl
phy[1].powerLevel = -10.0
phy[2].powerLevel = -10.0
phy[3].powerLevel = -10.0
phy.signalPowerLevel = -10.0
> plvl -20
OK
> plvl
phy[1].powerLevel = -20.0
phy[2].powerLevel = -20.0
phy[3].powerLevel = -20.0
phy.signalPowerLevel = -20.0
```

The `plvl` command simply displays or sets the `powerLevel` parameter of all channels. The same can be manually accomplished by setting or getting individual parameters, if desired:

```
> phy[1].powerLevel
-20
> phy[1].powerLevel = -10
-10
> phy[1].powerLevel
-10
> plvl
phy[1].powerLevel = -10.0
phy[2].powerLevel = -20.0
phy[3].powerLevel = -20.0
phy.signalPowerLevel = -20.0
```

While `plvl` seems like a command to just set/get a `powerLevel` parameter, it does that for several channels in one go. This can save you a lot of time and typing — to achieve the same thing manually, you'd be typing 4 commands!

3.2. Interacting with agents using messages

While you can access a lot of functionality via parameters and commands, to fully harness the power of UnetStack, we require an understanding of the underlying messaging system between the agents. All agents support messages that expose their functionality. In fact, all parameters and commands are implemented by exchanging messages between the shell agent and other agents. In this section, we'll take a brief look at how messaging between agents works.

All parameters and commands are implemented by exchanging messages between the shell agent and other agents. When you get/set a parameter, all the shell is doing is sending a `ParameterReq` message to the appropriate agent, and showing you the `ParameterRsp` message that the agent responds with.

Typically, we would want to send a *request* to an agent and get a *response* message back. This can be accomplished with the `request` call (or the equivalent alias `<<`) on the agent:

```
> phy << new TxFrameReq(data: [1,2,3])
AGREE
phy >> TxFrameNtf:INFORM[type:CONTROL txTime:2913909740]
```

Here we made a request to the `phy` agent to transmit some data. The agent responded with an `AGREE` response, shortly followed by a `TxFrameNtf` notification from `phy` telling us that the transmission was successful.

A *frame* is simply a datagram at the physical layer, also sometimes called a "packet". We prefer the term "frame" when working at the physical layer, but the distinction between frames and datagrams is unimportant at this point in time. We will come back to this later, in Chapter 14.

We can also use the return value in a condition, but we need to remember that the return value from the `request` is a message:

```
> x = phy << new TxFrameReq();
phy >> TxFrameNtf:INFORM[type:CONTROL txTime:3381446740]
> x
AGREE
> x.class
class org.arl.fjage.Message
> x.performative
AGREE
> if (x.performative == Performative.AGREE) print 'OK'
OK
```

The semicolon ";" at the end of the first statement prevents the return value from being printed on the shell.

Unsolicited notification messages can be received by subscribing to the topic of interest. For example, on node B, we can subscribe to physical layer events on node B:

```
> subscribe phy
```

Now, if we broadcast a frame from node A using `phy << new TxFrameReq()`, we will see the relevant reception events on node B:

```
phy >> RxFrameStartNtf:INFORM[type:CONTROL rxTime:1765508396]
phy >> RxFrameNtf:INFORM[type:CONTROL from:232 rxTime:1765508396]
```

The first event `RxFrameStartNtf` is triggered as soon as the frame is detected at node B. The second event `RxFrameNtf` is triggered when the frame is fully received, demodulated and successfully decoded at the receiver.

If all of this seems somewhat confusing to you, don't worry about it. Most of the basic functionality of the

stack can be accessed without having to deal with messages directly. As we need functionality that requires an understanding of messaging, we'll gradually introduce them in later chapters.

3.3. Shell scripting

The default UnetStack shell accepts any Groovy code, and so is very flexible:

```
> 1+2
3
> 5.times { print it }
0
1
2
3
4
```

You can also define closures (if you're not familiar with closures, you can think of them as functions for now):

```
> tx2 = {
-   2.times {
-     phy << new TxFrameReq()
-   }
- };
```

and call them later:

```
> tx2
phy >> TxFrameNtf:INFORM[type:CONTROL txTime:3911898740]
phy >> TxFrameNtf:INFORM[type:CONTROL txTime:3912307740]
```

You can write Groovy scripts and store them in the `scripts` folder with an extension `.groovy`. You can then invoke them from the shell by simply typing the name of the script (without the extension).

This only scratches the surface of what the command shell is capable of. However, it should provide you a basic understanding of how the shell works, and illustrate its power. To understand more, we suggest that you explore the online `help`. As you further understand the UnetStack and fjåge API, you'll develop expertise on using the shell.

Part II: Setting up underwater networks

Chapter 4. Unet basics

Now that we have a basic understanding of how UnetStack works, it is time to take the next step into setting up and configuring underwater networks, or simply *Unets*.

4.1. Node names and addresses

Unet nodes are identified by unique addresses within the Unet. Small Unets might use 8-bit addresses, supporting up to 255 different nodes. Larger Unets might use 16-bit addresses, supporting up to 65535 different nodes in the network. The address space is controlled by the parameter `node.addressSize`, and must be set to the same value (either 8 or 16) on all nodes in a Unet.

The code examples in this chapter assume that you have a simulated Unet (the 2-node-network simulation from Chapter 2) running, and you're connected to the shell of one of the nodes. However, if you have access to modems, you may choose to use the real Unet and connect to the shell of one of the modem nodes.

To check the current address size on your node:

```
> node
<<< NodeInfo >>>

[org.arl.unet.nodeinfo.NodeInfoParam]
  nodeName = A
  address = 232
  addressSize = 8
  canForward = true
  mobility = false
  location = [0.0, 0.0, -15.0]
  origin = [NaN, NaN]
```

Some node parameters have not been shown in the above listing for brevity.

Address 0 is a broadcast address. All other addresses may be assigned to nodes in a Unet. Each Unet node is also associated with a node name (`node.nodeName`). If a node name is not explicity set, it defaults to the string representation of the node address. Descriptive node names may be used, if desired:

```
> node.nodeName = 'buoy_A'
buoy_A
> node
<<< NodeInfo >>>

[org.arl.unet.nodeinfo.NodeInfoParam]
  nodeName = buoy_A
  address = 232
  addressSize = 8
  canForward = true
  mobility = false
  location = [1000.0, 0.0, -15.0]
  origin = []
```

It is recommended that, if descriptive node names are used, the corresponding node addresses be set

using the ADDRESS_RESOLUTION service. This ensures that name-to-address resolution leads to the correct address for the node. The ADDRESS_RESOLUTION service can be accessed via the `host()` shell command:

```
> host('buoy_A')
68
> node.address = host(node.nodeName)
68
```

The default ADDRESS_RESOLUTION agent in the UnetStack maps node names to node addresses using a hash function. The method reduces network traffic for host name resolution, but can lead to address conflicts between nodes if two names happen to map to the same address. It is the responsibility of the network engineer to resolve address conflicts manually during the setup of the network, if the default ADDRESS_RESOLUTION agent is used. For small networks, this is simply a matter of checking that all chosen node names in the network lead to unique node addresses:

```
> ['buoy_A', 'auv_1', 'auv_2', 'sensor_adcp1', 'sensor_ctd1'].each { name ->
-   print "${name}: ${host(name)}"
- };
buoy_A: 68
auv_1: 150
auv_2: 109
sensor_adcp1: 43
sensor_ctd1: 14
```

4.2. Protocol numbers

Datagrams represent packets of data sent between nodes. Each node may have multiple agents and applications running on it, and so we need a way to specify which application the datagram is meant for. To aid with this, each datagram is associated with a protocol number that identifies the consumer on the destination node that the datagram is intended for. The consumer may be an agent or an end-user application. Protocol numbers can be thought of as port numbers in TCP/IP or UDP/IP.

The consumer may be an agent or an end-user application. Protocol number 0 (`Protocol.DATA`) is used for generic application data. Protocol numbers from 1 to `Protocol.USER-1` (31) are reserved for use by default stack agents. Protocol numbers from `Protocol.USER` (32) to `Protocol.MAX` (63) are available for end-user applications to use.

On node B, type:

```
> s = new UnetSocket(this);
> s.bind(Protocol.USER)                // listen for datagrams with Protocol.USER
> rx = s.receive()
```

to wait for a reception with `Protocol.USER`.

On node A, type:

```
> s = new UnetSocket(this);
> s.connect(host('B'), Protocol.DATA)  // send datagrams with Protocol.DATA
> s.send('hi!' as byte[])
> s.connect(host('B'), Protocol.USER)  // send datagrams with Protocol.USER
> s.send('hello!' as byte[])
true
> s.close()
```

Node B will receive only the second message, since it is listening for datagrams with `Protocol.USER` only. We can confirm this by checking the data in the received datagram on the command shell for node B, and close the socket:

```
DatagramNtf:INFORM[from:68 to:31 protocol:32 (6 bytes)]
> new String(rx.data)
hello!
> s.close()
```

Chapter 5. Setting up small networks

5.1. Netiquette testbed

The Netiquette testbed in Singapore is a 3-node network that is deployed at sea (see Figure 4), and accessible over the Internet. Nodes A and B are cabled seabed mounted nodes, while node C is a solar-powered buoy. We use a simulated version of the Netiquette testbed to learn how to set up and operate small networks.

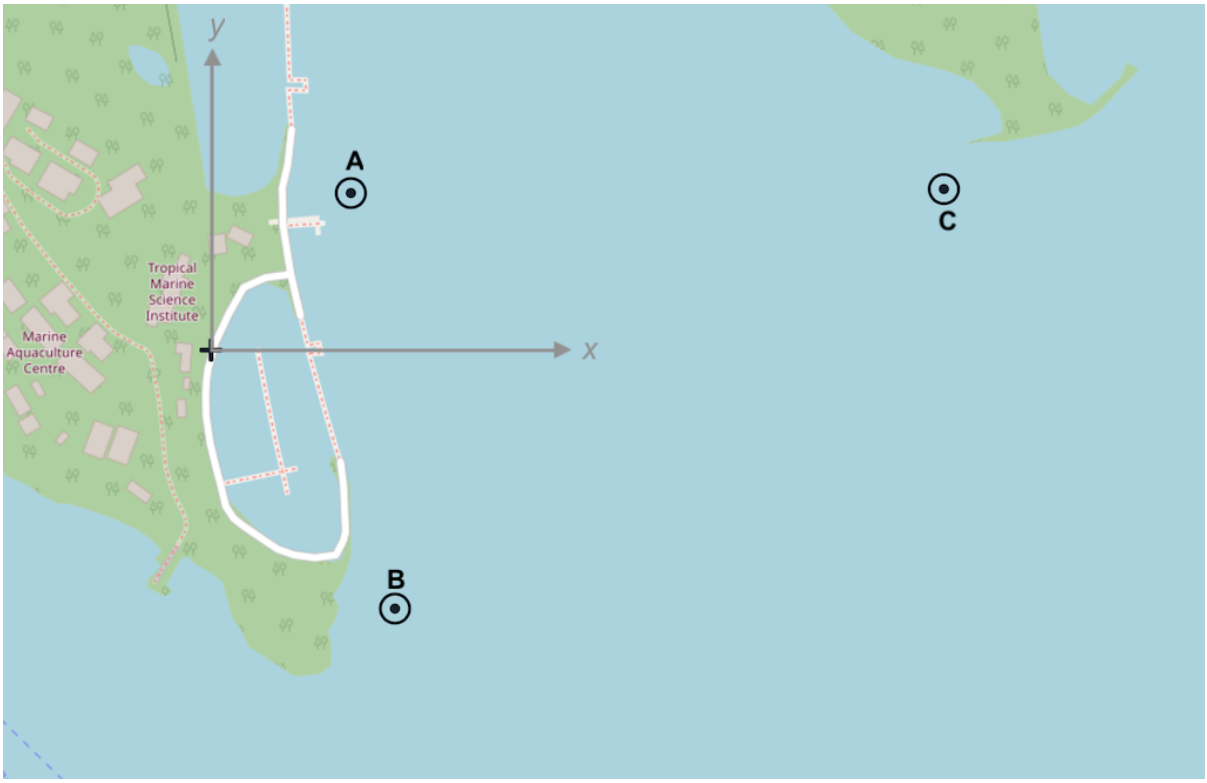


Figure 4. Netiqutte testbed

To start the simulated network, we simply run the `netq-network.groovy` simulation script:

```
$ bin/unet samples/netq-network.groovy

Netiquette 3-node network
-------------------------

Node A: tcp://localhost:1101, http://localhost:8081/
Node B: tcp://localhost:1102, http://localhost:8082/
Node C: tcp://localhost:1103, http://localhost:8083/
```

The port numbers you see in the examples above aren't particularly special. They are simply whatever were chosen by the developer of the simulation, and can be found in the `netq-network.groovy` script. The only restriction on the choice is that placed by the OS — usually port numbers below 1024 are *reserved* and unavailable to users. Of course, they must also be unique and unused by other applications running on your computer.

5.2. Node names & addresses

We start off by checking the configuration of each node:

Node A

```
> node
<<< NodeInfo >>>

[org.arl.unet.nodeinfo.NodeInfoParam]
  address = 232
  addressSize = 8
  location = [121.0, 137.0, -10.0]
  mobility = false
  nodeName = A
  origin = [1.216, 103.851]
```

Node B

```
> node
<<< NodeInfo >>>

[org.arl.unet.nodeinfo.NodeInfoParam]
  address = 31
  addressSize = 8
  location = [160.0, -232.0, -15.0]
  mobility = false
  nodeName = B
  origin = [1.216, 103.851]
```

Node C

```
> node
<<< NodeInfo >>>

[org.arl.unet.nodeinfo.NodeInfoParam]
  address = 74
  addressSize = 8
  location = [651.0, 140.0, -5.0]
  mobility = false
  nodeName = C
  origin = [1.216, 103.851]
```

All nodes are configured to use 8-bit addresses. Node A has is address 232, node B is 31, and node C is 74. The origin is set to GPS location 1.216° N, 103.851° E. Locations are measured in meters relative to this origin, with *x* axis pointing east, and *y* axis pointing north. The mobility of the nodes is set to `false` to indicate that the nodes are static (for mobile nodes, mobility should be set to `true`).

In the simulated network, all of the node parameters are correctly setup by the simulator. In a real network, you may need to setup each node by manually setting the appropriate parameters. To ensure that the nodes retain the parameters between reboots, once a node is setup, simply run `savestate` on the node. This creates a `savedstate.groovy` file in the `scripts` folder with the saved settings. The settings are then automatically loaded when the node is rebooted.

5.3. Connectivity & ranging

Let us first check the connectivity between the nodes:

Node A

```
> ping host('B')
PING 31
Response from 31: seq=0 rthops=2 time=2507 ms
Response from 31: seq=1 rthops=2 time=2852 ms
Response from 31: seq=2 rthops=2 time=2852 ms
3 packets transmitted, 3 packets received, 0% packet loss
> ping host('C')
PING 74
Response from 74: seq=0 rthops=2 time=2600 ms
Response from 74: seq=1 rthops=2 time=2634 ms
Response from 74: seq=2 rthops=2 time=2737 ms
3 packets transmitted, 3 packets received, 0% packet loss
```

The connectivity from node A to nodes B and C looks good. What about the connectivity from node B to node C?

Node B

```
> ping host('C')
PING 74
Response from 74: seq=0 rthops=2 time=2810 ms
Response from 74: seq=1 rthops=2 time=2666 ms
Response from 74: seq=2 rthops=2 time=2742 ms
3 packets transmitted, 3 packets received, 0% packet loss
```

Looks good too!

In this simulation, everything checks out nicely. But, in the real world, there may be packet loss to contend with. We will see how to handle those in later chapters.

We can also check cross-check that the routes from node A to nodes B and C are direct:

Node A

```
> trace host('B')
[232, 31, 232]
> trace host('C')
[232, 74, 232]
```

The first trace shows that the datagram originated at node A (address 232), reached node B (address 31), and was sent back to node A. The second trace similarly went from node A to node C (address 74) and back. No hops in between, since our network is fully connected.

We can also make range measurements (in meters) between the nodes:

Node A

```
> range host('A')
0.0
> range host('B')
370.98
> range host('C')
529.87
```

Node B

```
> range host('A')
370.98
> range host('B')
0.0
> range host('C')
615.9
```

5.4. Sending text messages

Once we have connectivity, we can of course send text messages from the shell:

Node A

```
> tell host('B'), 'hello!'
AGREE
```

and we see the text message on node B:

Node B

```
[232]: hello!
```

We have already seen in Chapter 2 and Section 4.2 on how to send text messages using the UnetSocket API from the shell, as well as from external applications. Hence we won't dwell on it here.

5.5. File transfer and remote access

Data is often stored in files. Transferring files between nodes is a common requirement. File transfers and remote access is disabled by default. Let us enable this on node B:

Node B

```
> remote
<<< RemoteControl >>>

[org.arl.unet.remote.RemoteControlParam]
  cwd = /Users/mandar/Projects/unet/scripts
  dsp = transport
  enable = false
  reliability = true
  shell = websh
  groovy = true

> remote.enable = true
true
```

Now we can send & receive files, and run remote commands on node B. Let's try it from node A:

Node A

```
> B = host('B')
31
> rsh B, 'tell me,"hi!"'              ①
AGREE
[31]: hi!                             ②
> file('abc.txt').text = 'demo';      ③
> ls                                  ④
abc.txt [4 bytes]
README.md [96 bytes]
> fput B, 'abc.txt'                   ⑤
AGREE
```

① Ask node B to send a "hi!" back to me. The variable `me` is automatically defined to be the source node address during the execution of the shell command when Groovy extensions are enabled (`remote.groovy = true`).

② On node A, we receive a "hi!" after a short delay.

③ Create a file `abc.txt` with `demo` as content.

④ List local files to check that we have a 4-byte file called `abc.txt`.

⑤ Send file `abc.txt` to node B.

On the shell for node B, we see the notification that the file `abc.txt` was successfully received:

Node B

```
remote >> RemoteFileNtf:INFORM[from:232 filename:abc.txt (4 bytes)]
```

Although we demonstrated file transfers between nodes with the simulator, all simulated nodes are running on your machine and so sharing the filesystem. When the file `abc.txt` was transferred from node A to B, the same file was simply overwritten, since it was created in the same folder. You could easily verify this by checking the modification time of the file on the filesystem before and after the transfer.

You can also use `fget` to receive a file from a remote node, but you have to remember to set

`remote.enable = true` on the receiving node:

Node A

```
> remote.enable = true
true
> fget B, 'abc.txt'
AGREE
remote >> RemoteFileNtf:INFORM[from:31 filename:abc.txt (4 bytes)]
> fget B, 'def.txt'
AGREE
remote >> RemoteFailureNtf:INFORM[RemoteFileGetReq:REQUEST[to:31 filename:def.txt] reason:no-file]
```

The last command failed to get file `def.txt`, as it does not exist on node B.

When we send commands to execute on a remote node, they are usually silently executed and the output is not sent back. If we want the output to be shown to us, we need to explicity ask for it using `tell`. Since this is often required, we have a simple Groovy extensions shortcut `?` to do this for us:

Node A

```
> rsh B, 'tell me,node.nodeName'
AGREE
[31]: B
> rsh B, '?node.nodeName'
AGREE
[31]: B
> rsh B, '?ls'
AGREE
[31]: abc.txt [4 bytes]
README.md [96 bytes]
> rsh B, '?1+2'
AGREE
[31]: 3
> rsh B, '?"You are ${me}, I am ${node.address}"'
AGREE
[31]: You are 232, I am 31
> rsh B, '?range '+host('C')
AGREE
[31]: 615.9
```

Sometimes we are not interested in the output, but simply want an acknowledgement that the command was successfully executed. For example, if we set the transmission power on a remote node, we want to know that it was set. That can be requested using the `ack` function.

Node A

```
> ack on
> rsh B, 'plvl -6'
AGREE
remote >> RemoteSuccessNtf:INFORM[RemoteExecReq:REQUEST[to:31 command:plvl -6 ack:true]]
> ack off
```

5.6. Node locations & coordinate systems

As seen in Section 5.2, some network nodes may know their own locations. This is useful for location-

based routing and other applications. Depending on the application needs, we may wish to use different coordinate systems when setting up a network. There are 4 basic options to choose from:

No coordinates

We do not know or care about each node's location.

Local coordinates

We wish to work in a local coordinate system, with only relative locations of the nodes being important.

Georeferenced local coordinates

We wish to work in a local coordinate system, with relative node locations specified in local coordinates. The GPS coordinate of the origin of the local coordinate system is specified.

GPS coordinates

We wish to specify the GPS location of each node, without defining a local coordinate system.

When node locations are not accurately known, we can opt not to define any coordinate system. Local coordinate systems are preferred in applications where such a coordinate system can be agreed upon for the entire network. Range computation and localization is easier to do in local coordinates. GPS coordinates are used when node location is important, but a local coordinate system cannot be easily defined (e.g. ad hoc network with no prior knowledge of area of operation).

UnetStack supports all 4 options through a set of simple conventions:

No coordinates

`node.origin = []`, `node.location = []` for all nodes.

Local coordinates

`node.origin = [Float.NaN, Float.NaN]` for all nodes. `node.location = [x, y, z]` is specified as a 3-tuple in meters. The *z* axis points downwards (with sealevel being considered 0 m), but the *x* and *y* axes are arbitrarily chosen.

Georeferenced local coordinates

`node.origin = [latitude, longitude]` for all nodes, with latitude and longitude being the commonly agreed origin location. `node.location = [x, y, z]` is specified as a 3-tuple in meters. The *x* axis points east, *y* axis points north, and the *z* axis points downwards (with sealevel being considered 0 m).

GPS coordinates

`node.origin = []` for all nodes, and `node.location = [latitude, longitude, z]` where the *z* axis points downwards (with sealevel being considered 0 m).

The Unet simulator requires a local coordinate system to be defined, and so only local coordinates or georeferenced local coordinates must be used in the simulator.

In Section 5.3, we measured the acoustic range between nodes A and B to about about 371 m. We can check this against distance computed from the location of nodes A and B. We first get the location of node A:

Node A

```
> node.location
[121.0, 137.0, -10.0]
```

and then compute the distance to it on node B:

Node B

```
> distance(node.location, [121.0, 137.0, -10.0])
371.09
```

We see that it agrees well with the acoustic range!

It is often necessary to convert between the GPS coordinate system and the local coordinate system. To aid in this, UnetStack provides a set of utility functions:

Node A

```
> gps = new org.arl.unet.utils.GpsLocalFrame(node.origin);   // set origin GPS coordinates
> gps.toGps(node.location[0..1])                             // local to GPS
[1.217238981, 103.8520872]                                   // GPS coordinates of node A
> gps.toLocal(1.21723898, 103.8520872)                       // GPS to local
[120.9994, 136.9999]
> node.location
[121.0, 137.0, -10.0]
```

The `GpsLocalFrame` class has additional constructors and utility methods to work with GPS coordinates in degrees, minutes and seconds, if desired.

Chapter 6. Routing in larger networks

6.1. MISSION 2013 network

The MISSION 2013 experiment in Singapore featured a 7-node network that was deployed at sea (see Figure 5) for several weeks. The network operated in a challenging area with complex 3D bathymetry, several reefs and heavy shipping. During the experiment, we transmitted more than 40000 frames of data and collected statistics on communication performance across various links in the network. These performance statistics are embedded in the `Mission2013a` channel model in UnetStack. We use a simulated version of the MISSION 2013 network to learn how to set up and operate larger networks that require routing.

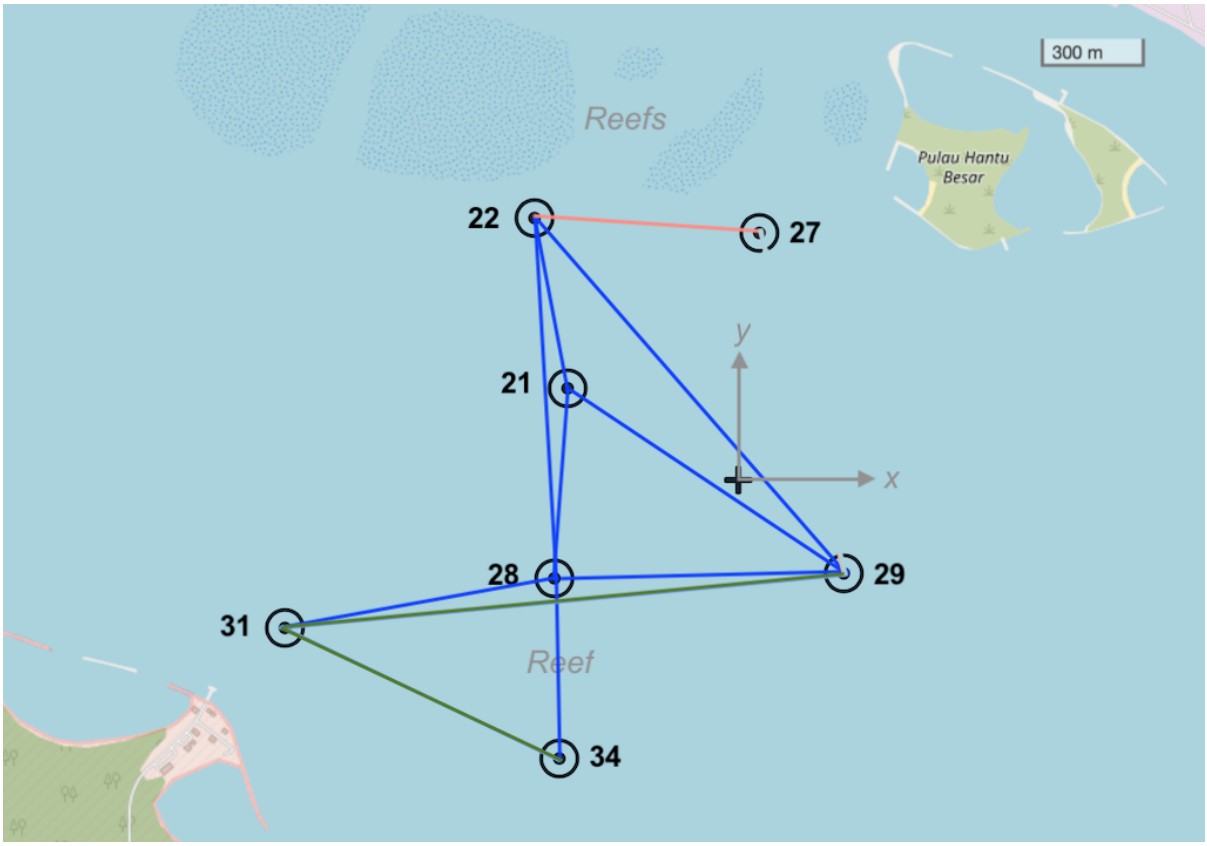


Figure 5. MISSION 2013 network

To start the simulated network, we simply run the `mission2013-network.groovy` simulation script:

```
$ bin/unet samples/mission2013-network.groovy

MISSION 2013 network
--------------------
Node 21: tcp://localhost:1121, http://localhost:8021/
Node 22: tcp://localhost:1122, http://localhost:8022/
Node 27: tcp://localhost:1127, http://localhost:8027/
Node 28: tcp://localhost:1128, http://localhost:8028/
Node 29: tcp://localhost:1129, http://localhost:8029/
Node 31: tcp://localhost:1131, http://localhost:8031/
Node 34: tcp://localhost:1134, http://localhost:8034/
```

While the MISSION 2013 network is not physically very large (only about 1.5 km across), the challenging

environment kept the network from being fully connected, i.e., not all nodes could directly communicate with all others. The average frame delivery ratio (number of successfully delivered frames / number of transmitted frames) on each link is shown in Table 2. The link quality is also shown on the map in Figure 5, with dark blue links being the good ones, dark green ones being the weak ones, and brownish one being the very poor link.

Table 2. Average frame delivery ratio for MISSION 2013 network

To: From:	**21**	**22**	**27**	**28**	**29**	**31**	**34**
21	-	0.926	0.266	0.917	0.912	0.000	0.552
22	0.867	-	0.471	0.751	0.850	0.000	0.288
27	0.359	0.381	-	0.313	0.322	0.000	0.000
28	0.847	0.869	0.390	-	0.845	0.925	0.863
29	0.539	0.693	0.333	0.688	-	0.374	0.000
31	0.000	0.000	0.000	0.902	0.805	-	0.795
34	0.236	0.436	0.000	0.684	0.000	0.544	-

6.2. Connectivity without routing

During the MISSION 2013 experiment, node 21 was a gateway node with surface expression and connectivity to the Internet (via a 3G cellular network). All other nodes were on the seabed and not directly accessible. So let us start by exploring the connectivity from node 21 to other nodes:

Node 21

```
> ping 22
PING 22
Response from 22: seq=0 rthops=2 time=10609 ms
Response from 22: seq=1 rthops=2 time=2656 ms
Response from 22: seq=2 rthops=2 time=2739 ms
3 packets transmitted, 3 packets received, 0% packet loss
> ping 27
PING 27
Request timeout for seq 0
Response from 27: seq=1 rthops=2 time=2960 ms
Request timeout for seq 2
3 packets transmitted, 1 packets received, 67% packet loss
> ping 28
PING 28
Response from 28: seq=0 rthops=2 time=2725 ms
Response from 28: seq=1 rthops=2 time=3036 ms
Response from 28: seq=2 rthops=2 time=3158 ms
3 packets transmitted, 3 packets received, 0% packet loss
> ping 29
PING 29
Response from 29: seq=0 rthops=2 time=3456 ms
Response from 29: seq=1 rthops=2 time=3298 ms
Response from 29: seq=2 rthops=2 time=3515 ms
3 packets transmitted, 3 packets received, 0% packet loss
> ping 31
PING 31
Request timeout for seq 0
Request timeout for seq 1
Request timeout for seq 2
3 packets transmitted, 0 packets received, 100% packet loss
> ping 34
PING 34
Request timeout for seq 0
Response from 34: seq=1 rthops=2 time=19603 ms
Request timeout for seq 2
3 packets transmitted, 1 packets received, 67% packet loss
```

We see that the connectivity to nodes 22, 28 and 29 is good, that to nodes 27 and 34 is poor, and to node 31 is non-existent.

6.3. Static routing

From Figure 5 and Table 2, we see that node 28 has good connectivity to nodes 31 and 34, so perhaps we could relay datagrams via node 28. Although the link between 22 and 27 seems to be better than the rest, the connectivity to that node is generally poor. Let us set up the following routes:

- Relay data between nodes 21 and 31 via node 28
- Relay data between nodes 21 and 34 via node 28

On node 21, we add routes to nodes 31 and 34:

Node 21

```
> addroute 31, 28
> addroute 34, 28
> routes
1: to 31 via uwlink/28 [reliable, hops: 0, metric: 1.0]
2: to 34 via uwlink/28 [reliable, hops: 0, metric: 1.0]
```

On nodes 31 and 34, we add routes to node 21 via node 28:

Node 31

```
> addroute 21, 28
> routes
1: to 21 via uwlink/28 [reliable, hops: 0, metric: 1.0]
```

Node 34

```
> addroute 21, 28
> routes
1: to 21 via uwlink/28 [reliable, hops: 0, metric: 1.0]
```

Now, we can check out connectivity from node 21 to nodes 31 and 34 again:

Node 21

```
> ping 31
PING 31
Response from 31: seq=0 rthops=4 time=15245 ms
Response from 31: seq=1 rthops=4 time=10673 ms
Response from 31: seq=2 rthops=4 time=10779 ms
3 packets transmitted, 3 packets received, 0% packet loss
> ping 34
Response from 34: seq=0 rthops=4 time=26878 ms
Request timeout for seq 1
Request timeout for seq 2
3 packets transmitted, 1 packets received, 67% packet loss
```

While the connectivity to node 31 seems okay, the connectivity to node 34 is still poor. We notice that the `seq=0` round-trip time is very close to the timeout of 30 seconds, and so try a ping with a longer timeout of 60 seconds:

Node 21

```
> ping 34, 3, 60000
Response from 34: seq=0 rthops=4 time=38505 ms
Response from 34: seq=1 rthops=4 time=34393 ms
Response from 34: seq=0 rthops=4 time=22521 ms
3 packets transmitted, 3 packets received, 0% packet loss
```

Much better!

The pings to nodes 31 and 34 show `rthops` (round trip hops) to be 4, which makes sense, since we have 2-hop routes in each direction. We can ask the routing agent for a trace to check what route the datagram took:

Node 21

```
> trace 31
[21, 28, 31, 28, 21]
```

This shows that the datagram originated at node 21, passed through node 28 before reaching node 31. Then on the way back, it passed through node 28 again, and reached us back at node 21.

Let us next try to do something using the routes we created. We can get node 21 to ask node 31 to measure the range to node 34 and report it to us. This request will be relayed via node 28, since our routing tables are set up to do so. Remember to set `remote.enable = true` on node 31 before making the request from node 21:

Node 21

```
> rsh 31, '?range 34'
AGREE
[31]: 873.67
```

As you can see from Table 2, the connectivity between nodes 31 and 34 is poor in this simulated network. You may need to try this command several times before you get a range estimate. When the ranging fails, you should see the message "ERROR: No response from remote node" back from node 31, which by itself demonstrates successful routing.

If you don't have the patience to try a few times for range from node 31 to node 34, try getting a range from node 31 to 28, which will be much quicker: `rsh 31, '?range 28'`.

6.4. Route discovery

In the previous section, we learned how to set up static routes manually. But what if we are too lazy to determine the routes manually? Or if we don't have access to the nodes on the seabed to set up routes? We can use the route discovery agent to populate the routing tables.

To see how to do this, let us restart our MISSION 2013 simulation so that the routing tables are empty (alternatively we can remove the routes we created earlier by typing `delroutes` on nodes 21, 31 and 34). We can verify that the routing table is indeed empty:

Node 21

```
> routes
>
```

Now, start a route discovery to node 31:

Node 21

```
> rreq 31
OK
```

Patiently wait for a minute or two before checking the routing table on node 21:

Node 21

```
> routes
1: to 29 via uwlink/29 [reliable, hops: 1, metric: 2.0]
2: to 34 via uwlink/34 [reliable, hops: 1, metric: 2.0]
3: to 22 via uwlink/22 [reliable, hops: 1, metric: 3.0]
4: to 28 via uwlink/28 [reliable, hops: 1, metric: 5.0]
5: to 31 via uwlink/28 [reliable, hops: 2, metric: 0.85]
6: to 27 via uwlink/27 [reliable, hops: 1, metric: 1.0]
```

Your routing table may differ, as the route discovery process is stochastic. We see that we now have a route to node 31 via node 28. Let us check the routing table on node 31 as well, to see if it has a corresponding entry for a route to node 21:

Node 31

```
> routes
1: to 29 via uwlink/29 [reliable, hops: 1, metric: 2.0]
2: to 21 via uwlink/29 [reliable, hops: 2, metric: 1.7]
3: to 28 via uwlink/28 [reliable, hops: 1, metric: 5.0]
4: to 21 via uwlink/28 [reliable, hops: 2, metric: 4.2]
5: to 34 via uwlink/34 [reliable, hops: 1, metric: 2.0]
6: to 21 via uwlink/34 [reliable, hops: 3, metric: 1.6]
```

Indeed it does! In fact, it has 3 routes back to node 21, one via node 29, another via node 28 and the last via node 34. Of these routes, the route via node 28 has the largest metric, and so will be the route that is used. We can verify that by issuing a trace from node 21:

Node 21

```
> trace 31
[21, 28, 31, 28, 21]
```

Since the route discovery process is stochastic, it may be useful to repeat the route discovery if good routes are not established after a single try. The `rreq` command can also be called with parameters to control the repetition. For example `rreq 31, 3, 6, 30` will initiate 6 route discoveries to node 31 looking for up to 3-hop routes spaced by 30 seconds between discoveries.

Chapter 7. Wired and over-the-air links

The networks we explored in the last few chapters were completely underwater. All links were underwater acoustic links. If we wanted to replace some of the acoustic links with underwater optical or RF links, or even through-the-air cellular, WiFi or RF links, that could easily be done, as long as you had a modem driver (a specific type of agent) that supported the device that provided the link. Cellular, WiFi and other devices often already have TCP/IP network stacks running on them, to provide seamless connectivity to the Internet. UnetStack can leverage the existing network stack in these devices without having to develop new modem drivers, by translating Unet datagrams to UDP/IP datagrams, tunneling them through the IP network, and translating them back to Unet datagrams at the other end.

7.1. The UdpLink agent

The `UdpLink` agent offers the LINK service (Chapter 20) over an IP network.

To see how this works, let us revisit the MISSION 2013 network from Figure 5. Recall that node 21 was a gateway node with surface expression, and was connected to the Internet via a 3G cellular IP connection. During the experiment, we had no direct acoustic connectivity between nodes 21 and 31, and hence we routed all communication to node 31 via node 28.

Let us consider a scenario where node 31 also has a surface expression and 3G cellular IP connectivity. In this case, it would be nice to have a direct link from node 21 to node 31 via UDP/IP. Let's see how to set that up.

Fire up the `mission2013-network.groovy` network simulation (or if you already have it running from the last chapter, terminate and restart it, so that we have no routes in our routing tables). Connect to node 21's shell and add the `UdpLink` agent, and setup a route to node 31 via the UDP link:

Node 21:

```
> container.add 'udplink', new UdpLink();
> udplink
<<< UdpLink >>>

[org.arl.unet.DatagramParam]
  MTU = 1450

[org.arl.unet.link.LinkParam]
  dataRate = 0.0

[org.arl.unet.link.UdpLinkParam]
  monitorTimeout = 200
  multicastAddr = 239.0.0.1
  multicastIface = en0
  multicastPort = 5100
  multicastTTL = 1
  retries = 2
  timeout = 0.5

> addroute 31, 31, udplink
> routes
1: to 31 via udplink/31 [reliable, hops: 1, metric: 1.0]
```

Similarly, connect to node 31's shell and add the `UdpLink` agent as well as a route to node 21 via the UDP link:

Node 31:

```
> container.add 'udplink', new UdpLink();
> addroute 21, 21, udplink
> routes
1: to 21 via udplink/21 [reliable, hops: 1, metric: 1.0]
```

Go back to node 21's shell and see if you can communicate to node 31 via the UDP link:

Node 21:

```
> ping 31
PING 31
Response from 31: seq=0 rthops=2 time=18 ms
Response from 31: seq=1 rthops=2 time=1 ms
Response from 31: seq=2 rthops=2 time=2 ms
3 packets transmitted, 3 packets received, 0% packet loss

> ack on
> tell 31, 'hello'
AGREE
remote >> RemoteSuccessNtf:INFORM[RemoteTextReq:REQUEST[to:31 text:hello ack:true]]
```

and on node 31, you'll see:

Node 31:

```
[21]: hello
```

You'll also notice that the communication is much faster, since the UDP/IP latency is low and data rate is much higher.

7.2. Multilink routing

When we added the `UdpLink` agent in the last section, we set up static routes manually on both nodes. Let's delete these routes on both nodes:

Node 21, 31:

```
> delroutes
```

Now, let's see what the route discovery agent does when we ask it to discover routes for us:

Node 21

```
> rreq 31
OK
> routes      ①
1: to 31 via udplink/31 [reliable, hops: 1, metric: 1.0]
> routes      ②
1: to 29 via uwlink/29 [reliable, hops: 1, metric: 1.0]
2: to 31 via uwlink/29 [reliable, hops: 2, metric: 0.85]
3: to 22 via uwlink/22 [reliable, hops: 1, metric: 1.0]
4: to 31 via udplink/31 [reliable, hops: 1, metric: 3.0]
5: to 28 via uwlink/28 [reliable, hops: 1, metric: 2.0]
> trace 31    ③
[21, 31, 21]
```

① Checking routes within a few seconds after the `rreq`, we see that the route via the `udplink` is discovered very quickly.

② After a few minutes, we see that additional acoustic routes are also discovered (your routes may vary, as the route discovery is a stochastic process).

③ The route used for data transfer is the single-hop `udplink` route to node 31 and back.

Note that the route discovery resulted in 2 routes to node 31 in this case. The first one is an acoustic route (using `uwlink`) via node 29. The second one is a single-hop UDP (`udplink`) route. We can see that the metric for the 2-hop acoustic route is lower than that of the UDP route, and so the latter is used for data transfer. The metric is computed based on a combination of number of hops and the packet loss on a route.

You can check the routing table on node 31:

Node 31

```
> routes
1: to 29 via uwlink/29 [reliable, hops: 1, metric: 1.0]
2: to 21 via uwlink/29 [reliable, hops: 2, metric: 0.85]
3: to 21 via udplink/21 [reliable, hops: 1, metric: 3.0]
4: to 28 via uwlink/28 [reliable, hops: 1, metric: 2.0]
5: to 21 via uwlink/28 [reliable, hops: 2, metric: 1.7]
```

We see 3 routes (via node 29/`uwlink`, via node 28/`uwlink` and direct/`udplink`), and the route with the largest metric is still the `udplink` direct route.

Part III: Building Unet applications

Chapter 8. Interfacing with UnetStack

You now know how to set up a Unet. Let us next explore how you can go about interfacing your application with UnetStack to take advantage of the Unet. There are several options available:

- The **UnetSocket API** (Chapter 9) is the most convenient way of interface most modern applications with UnetStack. API bindings are available for many languages, including Java, Groovy, Python, Julia, Javascript and C. The API allows you to send and receive user data over the Unet, get and set agent parameters, and access advanced functionality by interacting with agents using messages.
- **UDP portals** (Section 10.1) provide a way to establish tunnels through the Unet for UDP datagrams. This facility can be used to transparently run applications that use UDP, over the Unet.
- **TCP portals** (Section 10.3) and **serial portals** (Section 10.4) provide a way to establish connection-oriented tunnels through the Unet. This is a simple way to run applications that communicate over a TCP/IP or serial port links, over the Unet.
- Many traditional modems provide an AT command set for applications to interact with them. While we do not encourage the use of AT commands (as they are error-prone and limited in functionality), it would be amiss not to mention that UnetStack also supports an **AT script engine** (Chapter 11) that may be used by legacy applications to interact with it using AT commands.

Chapter 9. UnetSocket API

The command shell is great for manual configuration and interaction, but often we require programmatic interaction from an external application. For this, we have the UnetSocket API (available in Java, Groovy, Python, Julia and C). While the exact syntax differs across languages, the basic concepts remain the same. We focus on the use of the API in Groovy in this section, but also show some examples in other languages.

9.1. Connecting to UnetStack

If you recall from Section 2.4, you opened a socket connection to UnetStack on the command shell with:

```
> s = new UnetSocket(this);
```

Since the command shell was running on the node you wanted to connect to, the meaning of `this` was clear. However, in general, you'll probably be running your application in a different process, or even on a different computer. You'll therefore need to provide details on how to connect to the node when opening a socket.

The examples in this chapter assume that you are running:
`bin/unet samples/2-node-network.groovy`

For example, to connect to UnetStack from an application over TCP/IP, we need to know the IP address and port of the API connector on UnetStack. Simply type `iface` on the command shell of node A to find this information:

```
> iface
tcp://192.168.1.9:1101 [API]
ws://192.168.1.9:8081/ws [API]
websh: ws://192.168.1.9:8081/fjage/shell/ws [GroovyScriptEngine]
```

The first entry starting with `tcp://` is the API connector available over TCP/IP. The IP address and port number in this case are `192.168.1.9` and `1102` respectively. The IP address on your setup might differ, so remember to replace it in the example code below when you try it.

To connect to UnetStack from a Groovy application, typical code might look something like this:

```
import org.arl.unet.api.UnetSocket

def sock = new UnetSocket('192.168.1.9', 1102)    ①
// do things with sock here
sock.close()
```

① Note that the `def` is typically not used in the shell, as we usually want the `sock` variable to be created in the shell's context. However, we use `def` in Groovy scripts or closures to keep the `sock` variable in the local context.

External applications interact with UnetStack via a UnetSocket API using fjåge's connector framework. This allows the API to access UnetStack over a TCP/IP connection, a serial port, or any other fjåge connector that may be available.

The code in other languages looks similar. For example, in Python:

```
from unetpy import UnetSocket

sock = UnetSocket('192.168.1.9', 1102)
# do things with sock here
sock.close()
```

A simple example application in Python using the UnetSocket API was illustrated previously in Section 2.5.

9.2. Sending data

To send datagrams using a socket, we first specify the destination address and protocol number using the `connect()` method, and then use the `send()` method to send data (byte array). In Groovy:

```
def to = sock.host('B')             ①
sock.connect(to, 0)                 ②
sock.send('hello!' as byte[])       ③
sock.send('more data!' as byte[])
```

① Resolve node name to address. If the destination address is already known, this step can be skipped.

② Connect using protcol 0 (generic data). Constant `org.arl.unet.Protocol.DATA` may be used instead of 0 for improved readability.

③ Data has to be converted into a `byte[]` for transmission using the `send()` method.

If only a single `send()` is desired, the `connect()` call may be omitted and the destination and protocol number can be provided as parameters to `send()`:

```
sock.send('hello!' as byte[], to, 0)
```

9.3. Receiving data

On the receiving end, we specify the protocol number to listen to using `bind()`, and then receive a datagram using the `receive()` method:

```
sock.bind(0)
def rx = sock.receive()
println(rx.from, rx.to, rx.data)
```

Unbound sockets listen to all unreserved protocols. So the `bind()` call above could be skipped, if we would like to listen to all application datagrams.

The `receive()` method above is blocking by default. The blocking behavior can be controlled using the `setTimeout()` method, where the blocking timeout can be specified in milliseconds. A timeout of 0 makes the call non-blocking. If no message is available at timeout, a `null` value is returned. When the `receive()` call is blocked, a call to `cancel()` can unblock and cause the `receive()` call to return immediately.

9.4. Getting & setting parameters

You have already been introduced to agent parameters in Chapter 3. Applications can obtain information about an agent by reading its parameters, and can control the behavior of the agent by modifying its parameters.

To access agent parameters, you first have to look up the relevant agent based on its name or a service that it provides. For example:

```
def phy = sock.agentForService(org.arl.unet.Services.PHYSICAL)   ①
println(phy.MTU)
println(phy[1].dataRate)
```

① Looking up an agent based on a services it provides is recommended, rather than specify the agent by name. We will explore services in more detail in Chapter 12. However, if you wished to reference an agent by name, you could have done that as: `def phy = sock.agent('phy')`

This will print the value of parameter `MTU` (maximum transfer unit) of the physical layer, and the physical layer `dataRate` of the CONTROL (1) channel. You could also change some of the parameters:

```
println(phy[2].frameLength)
phy[1].frameLength = 64
println(phy[2].frameLength)
```

Developers may wish to consider using constants `org.arl.unet.phy.Physical.CONTROL` and `org.arl.unet.phy.Physical.DATA` instead of hard coding 1 and 2, for readability.

The `phy` object that you received back from `sock.agentForService()` or `sock.agent()` is an `AgentID`. You can think of this as a reference to the agent. Setting and getting parameters on the agent ID sends `ParameterReq` messsages to the agent to read/modify the relevant parameters. You can also use agent IDs to send messages to the agent explicitly, as you will see next.

9.5. Accessing agent services

As we have already seen in Section 3.2, the full functionality of UnetStack can be harnessed by sending/receiving messages to/from various agents in the stack. We earlier saw how to do that from the shell. We now look at how to use the UnetSocket API to send/receive messages to/from agents.

To request broadcast of a CONTROL frame, like we did before from the shell, we need to lookup the agent providing the PHYSICAL service and send a `TxFrameReq` to it:

```
import org.arl.unet.phy.TxFrameReq

def phy = sock.agentForService(org.arl.unet.Services.PHYSICAL)
phy << new TxFrameReq()
```

For lower level transactions, we obtain a fjåge Gateway instance from the UnetSocket API, and use it directly. For example, we can subscribe to event notifications from the physical layer and print them:

```
def gw = sock.gateway
gw.subscribe(phy)
def msg = gw.receive(10000)     ①
if (msg) println(msg)
```

① Receive a message from the gateway with a timeout of 10000 ms. If no message is received during this period, `null` is returned.

9.6. Python and other languages

In Groovy and Java, services, parameters and messages are defined using enums and classes. These are made available to the client application by putting the relevant jars in the classpath. In other languages (e.g. Python, Julia, Javascript), services and parameters are simply referred to as strings with fully qualified names (e.g. `'org.arl.unet.Services.PHYSICAL'`). Messages are represented by dictionaries, but have to be declared before use.

For example, in Python:

```
from unetpy import *

sock = UnetSocket('192.168.1.9', 1102)
phy = sock.agentForService(Services.PHYSICAL)
phy << TxFrameReq()
sock.close()
```

If you recall from Section 2.5, `from` is a keyword in Python and so the `from` field in messages is replaced by `from_`. Other than this minor change, the fields in all the Python message classes are the same as the Java/Groovy versions.

Chapter 10. Portals

Although the UnetSocket API provides great flexibility, it requires an application to explicity use the API to integrate with UnetStack. Sometimes you might have devices or applications that talk to each other over a serial cable or a UDP/IP or TCP/IP connection, and you simply want to replace the cable or connection with an underwater wireless connection. Is there an easier way for such simple Internet or serial port applications to communicate over a Unet?

The answer lies in portals. A *portal* is a transparent connection across the Unet. Data going in through one end of the portal travels through the Unet and emerges from the other end. The interaction with the end points of the portal is via traditional technologies such as UDP/IP sockets, TCP/IP sockets, or serial ports. This enables applications developed to use these technologies to transparently work over a Unet.

Application examples

Imagine that you have a sensor that connects to a laptop over a RS232 serial cable. You want to deploy this sensor on the seabed and have its data be available wirelessly over the Internet in real time. All you want to do is replace that RS232 cable with a wireless Unet connection. A *serial portal* could be used for this. Instead of a RS232 serial cable, maybe the sensor published its data over an Ethernet cable on a TCP/IP port. You'd use a *TCP portal* instead.

In Section 10.2, we demonstrate a practical example of a video streaming application that runs over UDP, and can be made to transparently work over a Unet using the *UDP portal*.

While portals are easy to use, you should bear in mind that applications developed for the Internet or for use over serial ports do not understand the constraints and characteristics of a Unet. Some applications may use bandwidth inefficiently, or expect responses with latencies that are unreasonable for a Unet, and therefore perform poorly.

10.1. UDP portal

Since UDP is a datagram-oriented protocol, it is easy to map UDP datagrams to Unet datagrams. This is exactly what a UDP portal does, as shown in Figure 6.

In this example, application X sends a UDP datagram to node A, where a UdpPortal agent listens on UDP port 7000 (arbitrarily chosen port number). The UdpPortal agent converts the UDP datagram into a Unet datagram and sends it to node B. The UdpPortal agent on node B receives this datagram, converts is back to a UDP datagram and sends it to application Y listening on UDP port 7778 (also an arbitrarily chosen port number).

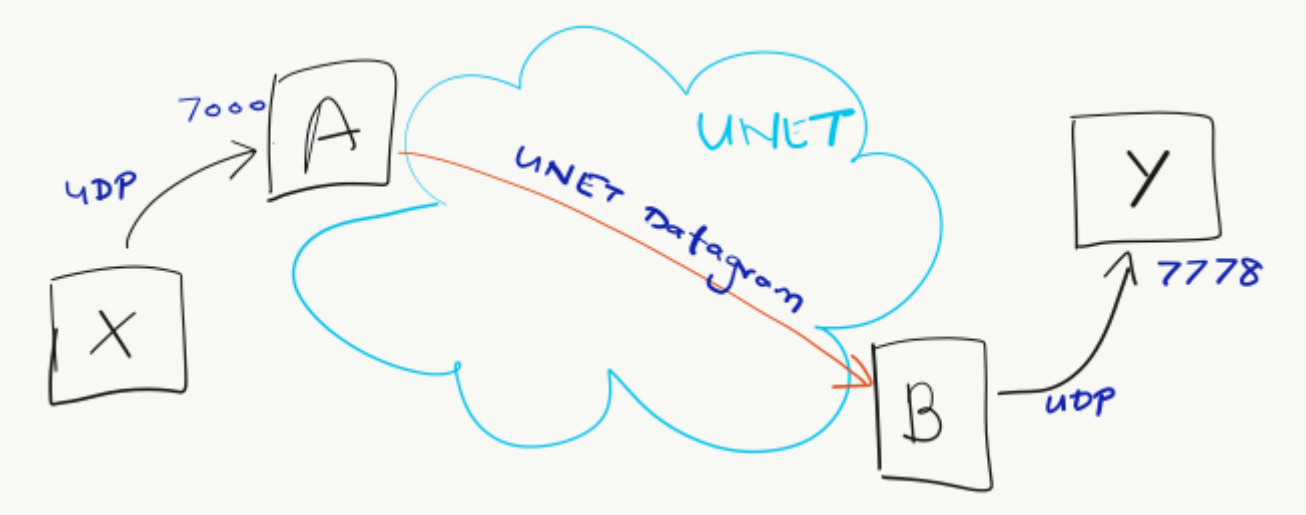


Figure 6. A UDP portal establishes a tunnel through the Unet for UDP datagrams to pass through.

Let us emulate this example with our favorite 2-node network. Fire up the 2-node network simulation, as before:

```
$ bin/unet samples/2-node-network.groovy

2-node network
--------------

Node A: tcp://localhost:1101, http://localhost:8081/
Node B: tcp://localhost:1102, http://localhost:8082/
```

Open browser windows for shell access to each of the nodes. On node A, create a UdpPortal listening on port 7000 (since application X will send UDP datagrams to this port) and sending Unet datagrams (protocol 0 in this example, but that can be configured using the `protocol` parameter below) to node B:

```
> container.add 'portal', new org.arl.unet.portal.UdpPortal(port:7000, peer:host('B'));
> portal
<<< UdpPortal >>>

[org.arl.unet.DatagramParam]
  MTU = 1500

[org.arl.unet.portal.UdpPortalParam]
  clientIP = 255.255.255.255
  clientPort = 7778
  link = uwlink
  peer = 31
  port = 7000
  priority = NORMAL
  protocol = 0
  reliability = false
```

The default `port` and `clientPort` for the UdpPortal are arbitrarily chosen to be 7777 and 7778 respectively. You can easily change them during creation of the UdpPortal, as we did above, or later, by setting the relevant parameter.

On node B, create the other end-point of the UDP portal to send the UDP datagrams to `localhost` UDP port 7778, where you will run application Y:

```
> container.add 'portal', new org.arl.unet.portal.UdpPortal(clientIP: 'localhost', clientPort: 7778);
> portal
<<< UdpPortal >>>

[org.arl.unet.DatagramParam]
  MTU = 1500

[org.arl.unet.portal.UdpPortalParam]
  clientIP = localhost
  clientPort = 7778
  link = uwlink
  peer = 0
  port = 7777
  priority = NORMAL
  protocol = 0
  reliability = false
```

That's it, your UDP portal is set up! Time to test it out!!

To test the UDP portal (and later, the TCP portal), we will use `netcat` or `nc`. If you don't have this installed on your machine, now would be a good time to go download and install it.

Open a terminal window on your machine and set up a simple UDP server listening on port 7778 (application Y):

```
$ nc -u -l 7778
```

Open another terminal window and set up a simple UDP client to send text datagrams to port 7000 (application X). Assuming your IP address is `192.168.1.9`, you can do this using the command shown below. Type a text message and press ENTER.

```
$ nc -u 192.168.1.9 7000
hello                           ①
```

① Type your text message "hello" followed by ENTER.

In a few seconds, you should see that text message appearing on application Y terminal:

```
$ nc -u -l 7778                 ①
hello                           ②
```

① You had already typed this in earlier.

② Your text message "hello" appears here.

The text message went through the Unet to get there!

You may need to use the IP address of your machine (e.g. `192.168.1.9`) for the UDP connection to send the text message, rather than `localhost`. This is because the UdpPortal binds to the default network interface, and not to the loopback network interface.

10.2. Video streaming using UDP portal

You can do some cool things once you have set up the UDP portal. Here's one real-life example:

Say, you wanted to stream video through the Unet. If you have `ffmpeg` installed, you can set up a UDP video client listening on port 7778:

```
$ ffplay udp://192.168.1.9:7778
```

and you can stream a video (`movie.m4v`) over UDP to port 7000:

```
$ ffmpeg -re -i movie.m4v -an -s cif -r 6 -c:v libx264 -b:v 15k -f mpegts udp://192.168.1.7:7000?pkt_size
=512
```

The various flags control the quality, frame rate, and encoding of the video, and the `pkt_size` option controls the size of the datagrams sent.

The `ffmpeg` flags need to be adjusted to suit your Unet (read the `ffmpeg` documentation!). You need to ensure that the links in the Unet can support the data rates needed for this video, based on the flags you select. We have demonstrated real-time video with a high-speed acoustic underwater link with data rates of about 40 kbps.

10.3. TCP portal

A TCP portal is set up using the Portal agent. The Portal agent is quite similar to the UdpPortal agent, but provides more flexibility through the fjåge connectors framework. We can use a TCP connector for our TCP portal.

Restart your 2-node network, and on node A set up a TCP portal listening on port 7000:

```
> container.add 'portal', new org.arl.unet.portal.Portal(7000);
> portal
<<< Portal >>>

[org.arl.unet.DatagramParam]
  MTU = 128

[org.arl.unet.portal.PortalParam]
  delimiters = [10, 13]
  link = uwlink
  peer = 0
  priority = NORMAL
  protocol = 0
  reliability = false
  timeout = 1000
```

On node B, create the other end-point of the TCP portal listening on port 7001:

```
> container.add 'portal', new org.arl.unet.portal.Portal(7001);
```

That's it, your TCP portal is set up! Time to test it out!!

Open a terminal window on your machine and connect over TCP/IP to node A:

```
$ nc localhost 7000
```

Open another terminal window and connect over TCP/IP to node B. Type a text message and press ENTER.

```
$ nc localhost 7001
hello                           ①
```

① Type in your text message "hello", and press ENTER.

In a few seconds, you should see that text message appearing on the TCP/IP connection to node A:

```
$ nc localhost 7000             ①
hello                           ②
```

① You had already typed this in above.

② Your text message "hello" appears here.

The text message went through the Unet to get there!

The TCP portal is bidirectional, so you can type something on node A, and you should see it appear on node B. The UDP portal in Section 10.1 can also be set up as bidirectional by carefully configuring the `peer`, `port`, and `clientPort` parameters at both end-points.

10.4. Serial portal

Since the Portal agent uses the fjåge connectors framework, it can easily work with any type of connector. Since fjåge provides a serial port connecor, we can easily set up a serial portal on each of your nodes:

```
> container.add 'portal', new org.arl.unet.portal.Portal('/dev/ttyS0', 9600, 'N81');
```

Since many modern computers do not have serial ports, you may not be able to test the above code on your computer. If you have underwater modems with serial ports, you'll need to replace the device name (`/dev/ttyS0`) with the appropriate serial port device name to run this code. You can also customize the serial port baud rate (`9600`) and settings (`N81`).

Once you have the serial portal set up on all nodes, you can connect to the node's serial port using a serial terminal application (e.g. `minicom`) and type text messages just like you did with `nc` during the TCP portal test.

Chapter 11. AT script engine

The UnetSocket API (Chapter 9) is the recommended way to integrate applications with UnetStack. The AT script engine is only provided for legacy system support, and its use should be avoided in modern systems, as they suffer from several drawbacks (serialized interaction, error prone parsing, limited flexibility, lack of scripting support, etc.)

The AT command interpreter provides support for legacy applications that prefer to interact with UnetStack using AT text commands. All AT commands begin on a fresh line with an `AT` prefix, and end with a new line (CR or LF). Spaces and other whitespace characters are considered significant. Lines without the `AT` command prefix are silently ignored and may be used as a comment in AT command files. All AT commands are case-insensitive, with the exception of Java class names and parameter names in the `AT~EXT` and `AT~MSG` commands.

A successful response to an AT command may span several lines of text followed by an `OK` to mark the end of the response. If the AT command is unsuccessful, an `ERROR` response is returned. The `OK` or `ERROR` response is also terminated by a new line (CR or LF).

Unsolicited notifications may be sent by the AT command interpreter to the user. Responses and notifications are atomic, and lines from each may not be interleaved in the other.

We describe the AT command set through examples below. The convention used in describing commands is that the command is in uppercase. Lowercase words denote parameters in the command, to be replaced by the user with appropriate values. Optional parts of the command are denoted by [...].

11.1. Starting the AT command interpreter

The AT command interpreter is available as a script engine that can be loaded using a shell agent:

```
> conn = new org.arl.fjage.connectors.TcpHubConnector(5001, false)        ①
> cshell = new org.arl.fjage.shell.ConsoleShell(conn, true)
> shell = new ShellAgent(cshell, new org.arl.unet.shell.ATScriptEngine())
> shell.addInitrc 'etc/atshrc.atc'                                        ②
> container.add 'at', shell
```

① The AT command interpreter is exposed over a TCP/IP connection on port 5001. The `conn` could easily be replaced by another type of connection (e.g. RS232 port), if desired.

② We added an initalization file `etc/atshrc.atc` in this example, so that some AT commands can automatically be run on startup.

11.2. Basic AT commands

A small set of basic AT commands are honored by the interpreter:

- `AT` — check if a command link is active:

```
AT
OK
```

- `ATE0`/`ATE1` — turn off/on echo:

```
ATE1
OK
AT
AT
OK
ATE0
ATE0
OK
AT
OK
```

- `ATZ` — shutdown/reboot
- `AT/` — repeat last AT command

11.3. Shell extensions

The interpreter can be customized using shell extensions:

- `AT~EXT=classname` — load shell extension

Fields and methods exposed by a shell extension are made available in a shell using this command. Example:

```
AT~PLVL
ERROR
AT~EXT=org.arl.unet.phy.PhysicalShellExt
OK
AT~PLVL
PHY/1.POWERLEVEL=-10.0
PHY/2.POWERLEVEL=-10.0
PHY/3.POWERLEVEL=-10.0
PHY/4.POWERLEVEL=-10.0
PHY.SIGNALPOWERLEVEL=-10.0
OK
AT~PLVL=-3
OK
AT~PLVL
PHY/1.POWERLEVEL=-3.0
PHY/2.POWERLEVEL=-3.0
PHY/3.POWERLEVEL=-3.0
PHY/4.POWERLEVEL=-3.0
PHY.SIGNALPOWERLEVEL=-3.0
OK
```

The parameters to methods are specified as a comma-separated list after the `=` symbol in the command (e.g. `-3` in `AT~PLVL=-3`). The parameters may be numeric (`int`, `long`, `float` or `double`), `boolean` represented by `0` or `1` as `false` and `true` respectively, or double-quoted strings (e.g. `"this is a string"`).

11.4. Agent parameter access commands

Agent parameters may be listed, read and written to:

- `AT~agent[/index]?` — list parameters:

```
AT~PHY?
PHY.SIGNALPOWERLEVEL=-10.0
PHY.RXENABLE=1
PHY.MAXPOWERLEVEL=0.0
PHY.MINPOWERLEVEL=-138.0
PHY.NOISE=-71.9
PHY.MTU=13
PHY.FULLDUPLEX=1
PHY.BUSY=0
PHY.RTC="Tue Jul 23 02:19:39 SGT 2019"
OK
AT~PHY/1?
PHY/1.FRAMELENGTH=18
PHY/1.FEC=3
PHY/1.MTU=13
PHY/1.DATARATE=52.554745
PHY/1.FRAMEDURATION=2.74
PHY/1.MODULATION="fhbfsk"
PHY/1.POWERLEVEL=-10.0
PHY/1.VALID=1
PHY/1.THRESHOLD=0.25
OK
```

- `AT~agent[/index].parameter?` — get parameter:

```
AT~PHY/1.FRAMELENGTH?
PHY/1.FRAMELENGTH=18
OK
```

- `AT~agent[/index].parameter=value` — set parameter:

```
AT~PHY/1.FRAMELENGTH=21
OK
AT~PHY/1.FRAMELENGTH?
PHY/1.FRAMELENGTH=21
OK
```

11.5. Sending and receiving messages

The command interpreter may make requests and receive message notification by defining the messages of interest and subscribing to appropriate topics:

- `AT~MSG:<msg>=<classname>:parameter[,parameter]⋯` — define message format

Message formats defined using this command are available for requests and also used for notifications. If a message is not defined, notifications of that message type are silently ignored. The following command defines a message `DRQ` of class `org.arl.unet.DatagramReq` with 3 parameters: `to`, `protocol` and

`data` in that order:

```
AT~MSG:DRQ=org.arl.unet.DatagramReq:to,protocol,data
OK
```

We also define other messages similarly:

```
AT~MSG:TXNTF=org.arl.unet.phy.TxFrameNtf:type,txTime
OK
AT~MSG:RXNTF=org.arl.unet.phy.RxFrameNtf:from,to,protocol,rxTime,data
OK
```

- `AT~agent<msg=parameter[,parameter]⋯` — make a request

Once we have defined the messages above, we can make a request to `PHY` to send a datagram to node 2 with protocol 0 and 3 bytes of data: `[1,2,3]`:

```
AT~PHY<DRQ=2,0,"010203"
OK
```

The notification for the datagram transmission completion will be displayed as an unsolicited notification:

```
~PHY>TXNTF=2,1994962099
```

The general notifications format as: `~agent>msg=parameter[,parameter]⋯`. If any of the parameters are `byte[]` or `float[]`, they are not included in the parameter list. Instead a colon (`:`) is added at the end of the line, and the data in hex follows on subsequent lines. Once the data ends, a period (`.`) is sent on a single line. If multiple parameters are arrays, the number of array parameters is given by the number of colons at the end of the line, and each array is terminated by a period, followed by the next array. An example is shown below:

```
~PHY>RXNTF=1,0,0,2095058353:
0102030405060708090A0B0C0D0E0F
1112131415161718191A1B1C1D1E1F
.
```

- `AT~SUB=topic[,subtopic]` — subscribe to a topic

Without subscribing to a topic, we see that the user is not notified about the reception of a frame, although the message type is already defined:

```
AT~PHY.FULLDUPLEX=1
OK
AT~PHY<DRQ=0,0,"010203"
OK
~PHY>TXNTF=2,2095026099
```

After subscribing to `PHY`, the received message is reported:

```
AT~SUB=PHY
OK
AT~PHY<DRQ=0,0,"010203"
OK
~PHY>TXNTF=2,2095026099
~PHY>RXNTF=1,0,0,2095058353:
010203
.
```

Here we see that the data from the `RXNTF` is included after the notification message as a **data block**. This is the case for all `byte[]` or `float[]` parameters. Each data block may span several lines, and is terminated by a period (`.`) on a line by itself. The number of data blocks to follow a notification is denoted by the number of colons (`:`) at the end of a notification.

- `AT~UNSUB=topic[,subtopic]` — unsubscribe from a topic:

```
AT~UNSUB=PHY
OK
AT~PHY<DRQ=0,0,"010203"
OK
~PHY>TXNTF=2,2095026099
```

11.6. Managing the data buffer

While data may be directly included in a request message, sometimes it is useful to load data into a data buffer first, and then use it multiple times for requests. This is managed using the following commands:

- `AT~DATA:` — load data buffer

Data is represented as a series of hexadecimal bytes, and may span many lines. Data entry is terminated by a period (`.`) on a line by itself:

```
AT~DATA:
010203
040506
.
OK
```

The above representation is convenient for `byte[]` parameters. However, the same representation is used for other data arrays, including `float[]`, where the IEEE floating point representation is used for the floating point number to be converted to a series of bytes.

An alternative data representation is useful for `float[]`, where the floating point numbers are directly specified:

```
AT~DATA:
1.54
0.78
5.92
2.00
.
OK
```

For this representation, it is necessary to have a decimal place (`.`) in each number, and each line to contain only one floating point number.

- `AT~DATA?` — check size of data buffer:

```
AT~DATA:
010203
040506
.
OK
AT~DATA?
6 bytes
OK
```

- `AT~CLRDATA` — clear data buffer:

```
AT~CLRDATA
OK
AT~DATA?
EMPTY
OK
```

To use the data buffer, we simply use `"DATA"` instead of the hexadecimal data in a message. For example:

```
AT~SUB=PHY
OK
AT~DATA:
010203
040506
.
OK
AT~PHY<DRQ=0,0,"DATA"
OK
~PHY>TXNTF=2,3738882099
~PHY>RXNTF=1,0,0,3738925936:
010203040506
.
```

Part IV: Understanding UnetStack services

Chapter 12. Services and capabilities

So far you've interacted with agents, checking and changing agent parameters, and sending and receiving messages. But how do you know which agents to send what messages to, and what agents support which parameters? The answer to this question lies in the concept of *services*.

12.1. Terminology

To fully understand services, we need to formally define a few terms, many of which you are already somewhat familiar with:

Agent

An agent is logical entity that implements a specific functionality of the network. Loosely, an agent maps to a layer in a traditional network stack, but is more flexible. Each agent has its own thread of execution, and all agents can be thought of as running concurrently. An agent is normally referenced using its *AgentID*. You may think of an AgentID as the name of an agent, or a reference to the agent.

Message

Agents interact with each other via messages. Agents can send and receive messages, and typically expose all their functionality as a set of messages that they will respond to. Messages are transmitted within the network stack on a node, and not between nodes in the network. Each message is tagged with a *performative* that summarizes the purpose of the message. Common performatives are `REQUEST`, `AGREE`, `REFUSE`, `FAILURE`, `NOT_UNDERSTOOD` and `INFORM`.

It is easy to confuse messages, datagrams and frames. Messages are used by agents on a node to interact with other agents on the same node. They are never transmitted! Datagrams are logical packets of data that are exchanged between nodes. Datagrams may be fragmented and reassembled, and thus one datagram does not necessarily map to one transmission. Physical layer datagrams are called frames; they form the basic unit of data exchanged between nodes.

Request

Request messages ask an agent to perform some task. Such messages are marked with the performative `REQUEST`, and it is a convention to name the message class with a suffix `Req` (e.g. `DatagramReq`, `ParameterReq`).

Response

When an agent receives a request, it must respond back to the requesting agent. Common responses are simply messages with the performative set to `AGREE`, `REFUSE`, `FAILURE` or `NOT_UNDERSTOOD`. An `AGREE` message confirms to the requester that the agent will perform the requested task. A `REFUSE` message tells the requester that the request cannot be performed. A `FAILURE` message, on the other hand, means that the agent should have been able to do the request under normal circumstances, but something went wrong. A `NOT_UNDERSTOOD` response is generated if the agent does not know how to deal with the request. Other than these simple messages, responses may sometimes contain more information. Such messages are respresented by message classes with a suffix `Rsp` (e.g. `ParameterRsp`), and may have a performative of `INFORM` to indicate that they contain information in response to the request.

Notification

Agents sometimes generate unsolicited information. This information is encapsulated in a notification message, typically with a performative `INFORM`. Notification messages may be sent to a specific agent, or on a topic.

Topic

A topic defines a publish-subscribe mechanism where an agent may publish some notifications, and other agents interested in those notifications may *subscribe* to the topic. Most agents have an unnamed topic associated with themselves, that other agents can subscribe to. For example, a link agent may subscribe to the topic of a physical layer agent to listen for incoming data frames from the physical layer.

Parameters

Most UnetStack agents publish a number of parameters associated with them. Parameters are key-value pairs that provide information about the agent (read-only parameters), or allow controlling the behavior of the agent (read-write parameters). Parameters are technically accessed via `ParameterReq` and `ParameterRsp` messages, but a simpler notation (`agent.parameter`) is also available to get/set parameters.

Service

A service is a collection of messages (requests, responses and notifications) and parameters that an agent honors. Agents publish the list of services they offer, and you can find agents through the services they advertise.

Capability

Services often define optional capabilities. These capabilities may be offered by some agents advertising a service, but may be omitted by others. An agent can be queried to check if it supports a specific capability using the `CapabilityReq` message.

If all of these terms pique your curiosity, you may wish to take a look at the fjåge documentation. fjåge is the underlying agent framework that UnetStack is built on. While we don't assume familiarity with fjåge in this handbook, your understanding of UnetStack would certainly be quicker if you were to invest in building that familiarity.

12.2. Finding service providers

In Section 9.5, we have already come across the `agentForService()` function that helps us find an agent that provides a specific service. In this section, we'll explore this a bit more.

Fire up your trusty 2-node network and connect to node A's shell:

```
> a = agentForService(org.arl.unet.Services.PHYSICAL);
> a.name
phy
```

We asked for an agent that provides the `org.arl.unet.Services.PHYSICAL` service, and UnetStack responded back with an agent ID of an agent that can provide you that service. The name of that agent on node A is `phy`.

But what if there were more than one agents capable of providing the same service? We can ask for the list of all agents that provide a service:

```
> agentsForService(org.arl.unet.Services.PHYSICAL)
[phy]
```

Well, there was only one agent providing the PHYSICAL service. Are there other services that multiple agents provide? Indeed, there are:

```
> agentsForService(org.arl.unet.Services.DATAGRAM)
[transport, router, uwlink, phy]
```

The DATAGRAM service is provided by several agents. If you were interested in all incoming datagrams, you'd need to subscribe to the topics of all these agents!

What would have happened if you only asked for `agentForService()` instead of `agentsForService()` for the DATAGRAM service? Try it:

```
> a = agentForService(org.arl.unet.Services.DATAGRAM);
> a.name
transport
```

Any one of the agents in the list is returned!

Ever wondered what we assigned the `a = agentForService(⋯)`, and then asked for `a.name` to see the name of the agent?

When you try to print an AgentID object on the shell, the shell tries to be helpful and queries the agent for all its parameters and displays them. In this case, we were only interested in the name and not all the parameters, so we asked the shell not to get the parameters by explicitly asking for just `a.name`.

You can also ask an agent for the list of services it provides:

```
> phy.services
[org.arl.unet.Services.PHYSICAL, org.arl.unet.Services.DATAGRAM, org.arl.unet.Services.BASEBAND]
```

or get a list of all services provided by all agents in the stack:

```
> services
org.arl.unet.Services.NODE_INFO: node
org.arl.unet.Services.PHYSICAL: phy
org.arl.unet.Services.REMOTE: remote
org.arl.unet.Services.TRANSPORT: transport
org.arl.unet.Services.ADDRESS_RESOLUTION: arp
org.arl.unet.Services.MAC: mac
org.arl.unet.Services.RANGING: ranging
org.arl.fjage.shell.Services.SHELL: websh
org.arl.unet.Services.DATAGRAM: transport router uwlink phy
org.arl.unet.Services.BASEBAND: phy
org.arl.unet.Services.LINK: uwlink
org.arl.unet.Services.ROUTING: router
org.arl.unet.Services.STATE_MANAGER: state
org.arl.unet.Services.ROUTE_MAINTENANCE: rdp
```

12.3. Checking capabilities

So let's say you looked up the list of agents that provide the DATAGRAM service:

```
> agentsForService(org.arl.unet.Services.DATAGRAM)
[transport, router, uwlink, phy]
```

If you wanted to send a datagram, how do you pick which one you'd rather use? Different agents may provide different optional capabilities. If you were specifically interested in a particular capability (e.g. reliability), you could ask the agent if it supported that:

```
> phy << new CapabilityReq(org.arl.unet.DatagramCapability.RELIABILITY)
DISCONFIRM
> uwlink << new CapabilityReq(org.arl.unet.DatagramCapability.RELIABILITY)
CONFIRM
```

Here, we asked `phy` if it can do reliable datagram delivery, and it said "no". Then we asked `uwlink`, and it confirmed that it can. If you needed reliable delivery of our datagram, you should choose the latter.

You can also ask an agent to list all its optional capabilities:

```
> transport << new CapabilityReq()
CapabilityListRsp:INFORM[PROGRESS,RELIABILITY,FRAGMENTATION,CANCELLATION]
```

The `transport` agent says it can do reliable datagram delivery, fragment & reassemble large datagrams (if necessary), report on the progress of large datagram transfers, and cancel datagram delivery half way through the process (if the user wishes to).

Another way you may choose a service provider is by checking its parameters. For example, the `MTU` parameter (defined in the DATAGRAM service) tells you what is the largest datagram the agent can deliver:

```
> phy.MTU
56
> uwlink.MTU
3145632
```

If you had a small datagram (56 bytes or less) to deliver, and you did not care about reliability, you could ask `phy` to deliver it for you. But, if your datagram was larger, even if you did not need reliability, you'd have to ask `uwlink` to deliver it for you.

The `MTU` parameter is the DATAGRAM service is actually `org.arl.unet.DatagramParam.MTU`. Since we only have one `MTU` parameter that `phy` advertises, there is no ambiguity in using `phy.MTU`. But if you wanted to explicitly ask for the parameter by its fully qualified name, you could send a `ParameterReq` for it: `phy << new ParameterReq().get(org.arl.unet.DatagramParam.MTU)`

12.4. Service list

The following services are currently defined in UnetStack:

Short name	Fully qualified name	Description	Read...
DATAGRAM	`org.arl.unet.Services.DATAGRAM`	Send and receive datagrams	Chapter 13
PHYSICAL	`org.arl.unet.Services.PHYSICAL`	Physical layer	Chapter 14
BASEBAND	`org.arl.unet.Services.BASEBAND`	Arbitrary waveform transmission & recording	Chapter 15
RANGING	`org.arl.unet.Services.RANGING`	Ranging & synchronization	Chapter 16
NODE_INFO	`org.arl.unet.Services.NODE_INFO`	Node & network information	Chapter 17
ADDRESS_RESOLUTION	`org.arl.unet.Services.ADDRESS_RESOLUTION`	Address allocation & resolution	Chapter 18
LINK	`org.arl.unet.Services.LINK`	Datagram transmission over a single hop	Chapter 20
MAC	`org.arl.unet.Services.MAC`	Medium access control	Chapter 19
ROUTING	`org.arl.unet.Services.ROUTING`	Routing of datagrams over a multihop network	Chapter 21
ROUTE_MAINTENANCE	`org.arl.unet.Services.ROUTE_MAINTENANCE`	Discovery & maintenance of routes in a multihop network	Chapter 21
TRANSPORT	`org.arl.unet.Services.TRANSPORT`	Datagram transmission over a multihop network	[Transport and reliability]
REMOTE	`org.arl.unet.Services.REMOTE`	Remote command execution, text messaging & file transfer	Chapter 23
STATE_MANAGER	`org.arl.unet.Services.STATE_MANAGER`	State persistence across node reboots	Chapter 24
SCHEDULER	`org.arl.unet.Services.SCHEDULER`	Sleep-wake scheduling for energy management	Chapter 25

Short name	Fully qualified name	Description	Read...
SHELL	`org.arl.fjage.shell.Services.SHELL`	Commmand execution & file management services	Chapter 26

You can enjoy reading more about these services in the next few chapters.

Chapter 13. Datagram service

`org.arl.unet.Services.DATAGRAM`

Unets are all about sending datagrams between nodes!

The DATAGRAM service is, therefore, one of the fundamental services that many agents provide. However, different agents have very different capabilities in terms of what they can do with datagrams. Let's take a look at what the service offers, and how to use it effectively.

13.1. Overview

13.1.1. Messages

Notation guide

Every request message requires a response. When describing request messages, we also specify what responses to expect, through the notation:

- *request message* ⇒ *possible response messages* — *short description*

On the other hand, notification messages do not have corresponding responses, so we only describe them:

- *notification message* — *short description*

Agents offering the DATAGRAM service support messages to transmit and receive datagrams:

- `DatagramReq` ⇒ `AGREE` / `REFUSE` / `FAILURE`
- `DatagramNtf` — sent to the agent's topic, when a datagram is received

13.1.2. Parameters

Agents offering the DATAGRAM service support the following parameter:

- `MTU` — maximum datagram size in bytes

13.1.3. Capabilities

Agents may support several optional capabilities:

FRAGMENTATION

Agents capable of fragmentation may break a datagram into smaller datagrams, transmit each of them across the network, and reassemble them on the peer node.

RELIABILITY

If an agent advertises relaibility, it is able to acknowledge the successful delivery of the datagram.

Reliability is enabled on a per-datagram basis by setting the `reliability` flag in the `DatagramReq`. Depending on whether the datagram could be successfully delivered or not, one of the following notifications is generated:

- `DatagramDeliveryNtf` — sent to requestor
- `DatagramFailureNtf` — sent to requestor

PROGRESS

Agents capable of reporting progress do so by periodically sending the following notification for long data transfers:

- `DatagramProgressNtf` — sent to requestor on the transmitting node, and agent's topic on the receiving node

CANCELLATION

If an agent supports cancellation, it honors the following request for stopping an ongoing data transfer:

- `DatagramCancelReq` ⇒ `AGREE` / `REFUSE` / `FAILURE` / `NOT_UNDERSTOOD` (if unsupported)

PRIORITY

Agents advertising this capability prioritize datagrams with higher `priority` indicated in the `DatagramReq`.

TTL

Agents that spool `DatagramReq` over extended periods of time usually advertise this capability. They discard `DatagramReq` that are undelivered after the time-to-live (`ttl` attribute of the `DatagramReq`) has expired.

13.2. Examples

Fire up your 2-node network again, and open two browser windows — one connecting to node A's shell, and the other to node B's shell.

On node B:

```
> agentsForService(org.arl.unet.Services.DATAGRAM)
[transport, router, uwlink, phy]
> phy.MTU
56
> uwlink.MTU
848
> uwlink << new CapabilityReq()
CapabilityListRsp:INFORM[RELIABILITY,FRAGMENTATION]
> subscribe uwlink
```

We obtained a list of agents which provide the DATAGRAM service. We checked the `MTU` of the `phy` and `uwlink` agents, and found them to be 56 bytes and 848 bytes respectively. We decided to use the `uwlink` agent to communicate over a single-hop link between node A and B, and checked its capabilities. We found that it supports reliability and fragmentation. We then decided to listen to all datagrams received

by node B's `uwlink` agent by subscribing to its topic.

On node A:

```
> uwlink << new DatagramReq(to: 31, data: new byte[64])                          ①
AGREE
> uwlink << new DatagramReq(to: 31, data: new byte[64], reliability: true)       ②
AGREE
uwlink >> DatagramDeliveryNtf:INFORM[id:4dda055e-a533-401f-89c8-a01065ca5d70 to:31]  ③
> uwlink << new DatagramReq(to: 37, data: new byte[64], reliability: true)       ④
AGREE
uwlink >> DatagramFailureNtf:INFORM[id:bc65e643-6161-4b06-913c-3ff4f6985d36 to:37]  ⑤
> uwlink << new DatagramReq(to: 0, data: new byte[64])                           ⑥
AGREE
> uwlink << new DatagramReq(to: 0, data: new byte[64], reliability: true)        ⑦
REFUSE: Reliability not supported for broadcast
> uwlink << new DatagramReq(to: 31, data: new byte[1024])                        ⑧
REFUSE: Data length exceeds MTU
```

① Send an unreliable datagram to node 31.

② Send a reliable datagram to node 31.

③ Successful delivery of reliable datagram reported.

④ Send a reliable datagram to node 37. Since node 37 does not exist in this network, this should eventually fail.

⑤ Delivery failure reported (after trying for a few minutes).

⑥ Broadcast an unreliable datagram.

⑦ Broadcast request for reliable datagram is refused, as reliability requires a response from peer node and therefore cannot be supported on broadcast.

⑧ Datagram transmission request for data larger than MTU is also refused.

If we look at the shell for node B, we should see the 3 successfully delivered datagrams:

```
uwlink >> DatagramNtf:INFORM[from:232 to:31 (64 bytes)]
uwlink >> DatagramNtf:INFORM[from:232 to:31 (64 bytes)]
uwlink >> DatagramNtf:INFORM[from:232 (64 bytes)]
```

Agent `uwlink` uses the PHYSICAL service (agent `phy`) to deliver the data. Since the `phy.MTU` is only 56 bytes, but our datagrams were 64 bytes, unbeknownst to us, the `uwlink` agent must have been fragmenting these datagrams and reassembling them on the other side!

13.3. Short-circuit delivery

We were able to successfully deliver datagrams from node A to node B in the examples in the previous section. We not only saw the `DatagramNtf` messages on node B, but also got `DatagramDeliveryNtf` on node A if `reliability` was enabled.

Let's try it again, but with a small difference. On node A:

```
> uwlink << new DatagramReq(to: 31, data: new byte[32])
AGREE
```

We transmitted a smaller datagram, and node A happily accepted it for delivery. However, if we look at the shell for node B, we don't see a DatagramNtf message corresponding to the datagram, even though you had already subscribed to uwlink! What's going on? Let's try it again, but this time enable reliability:

```
> uwlink << new DatagramReq(to: 31, data: new byte[32], reliability: true)
AGREE
uwlink >> DatagramDeliveryNtf:INFORM[id:4aaa86e5-9a56-46f8-bc1a-f6be33af03a4 to:31]
```

We see that the datagram was indeed delivered! And now, if we look at node B's shell, we'll see the delivery notification:

```
uwlink >> DatagramNtf:INFORM[from:232 to:31 (32 bytes)]
```

It seems that enabling reliability successfully delivered the datagram, but otherwise the DatagramNtf message did not appear on node B's shell! You can try this many times, and the result will be the same. So it can't be random packet loss in the network either. What's going on?

To try and troubleshoot this, let's subscribe to notifications from the phy agent to see if the data is arriving at the physical layer. On node B:

```
> subscribe phy
```

On node A, transmit the unreliable small datagram again:

```
> uwlink << new DatagramReq(to: 31, data: new byte[32])
AGREE
```

On node B, we now see a couple of notifications:

```
phy >> RxFrameStartNtf:INFORM[type:DATA rxTime:3956973678]
phy >> RxFrameNtf:INFORM[type:DATA from:232 to:31 rxTime:3956973678 (32 bytes)]
```

The first notification says that the physical layer detected the start of a data frame. The second notification is for a received frame with 32 bytes from node 232 to node 31. That's our datagram!!! But why is it delivered by phy and not uwlink, when it was sent by uwlink on node A? And why is it a RxFrameNtf instead of a DatagramNtf?

Let's solve the second mystery first. An RxFrameNtf is a subclass of DatagramNtf, so it is indeed a DatagramNtf message. We can easily verify this on node B:

```
> ntf
RxFrameNtf:INFORM[type:DATA from:232 to:31 rxTime:3956973678 (32 bytes)]
> ntf instanceof DatagramNtf
true
```

Variable `ntf` contains the last notification received. It is the `RxFrameNtf`, and it is indeed an instance of `DatagramNtf`. So, we indeed got the datagram on node B, and it was delivered as a `DatagramNtf` with the correct metadata.

But why was it sent on `phy` agent's topic and not `uwlink` agent's topic, like all other datagrams we transmitted?

This is due to an optimization known as **short-circuit delivery** (introduced in UnetStack 3), depicted in Figure 7. The `uwlink` agent on node A looked at the unreliable `DatagramReq` for 32 bytes and realized that it is within the `phy` agent's capability (no reliability needed, and the datagram size is less than `phy.MTU`) to deliver this without the help of the `uwlink` agent. It delegated the task to the `phy` agent, which in turn send the datagram to its peer on node B, and therefore it was delivered to us by the `phy` agent on node B. This delegation not only reduces computation, but more importantly reduces the overhead of link headers in the frame, and therefore save valuable bandwidth in a resource-constrained underwater network.

Short-circuit delivery is not only done by `uwlink`, but by all agents supporting the DATAGRAM service. If a downstream agent is capable of delivering the datagram, the delivery is delegated automatically.

As a result of short-circuit delivery optimization, you need to subscribe to **all** DATAGRAM service providers to receive `DatagramNtf` messages, and not just the one you send the datagram via.

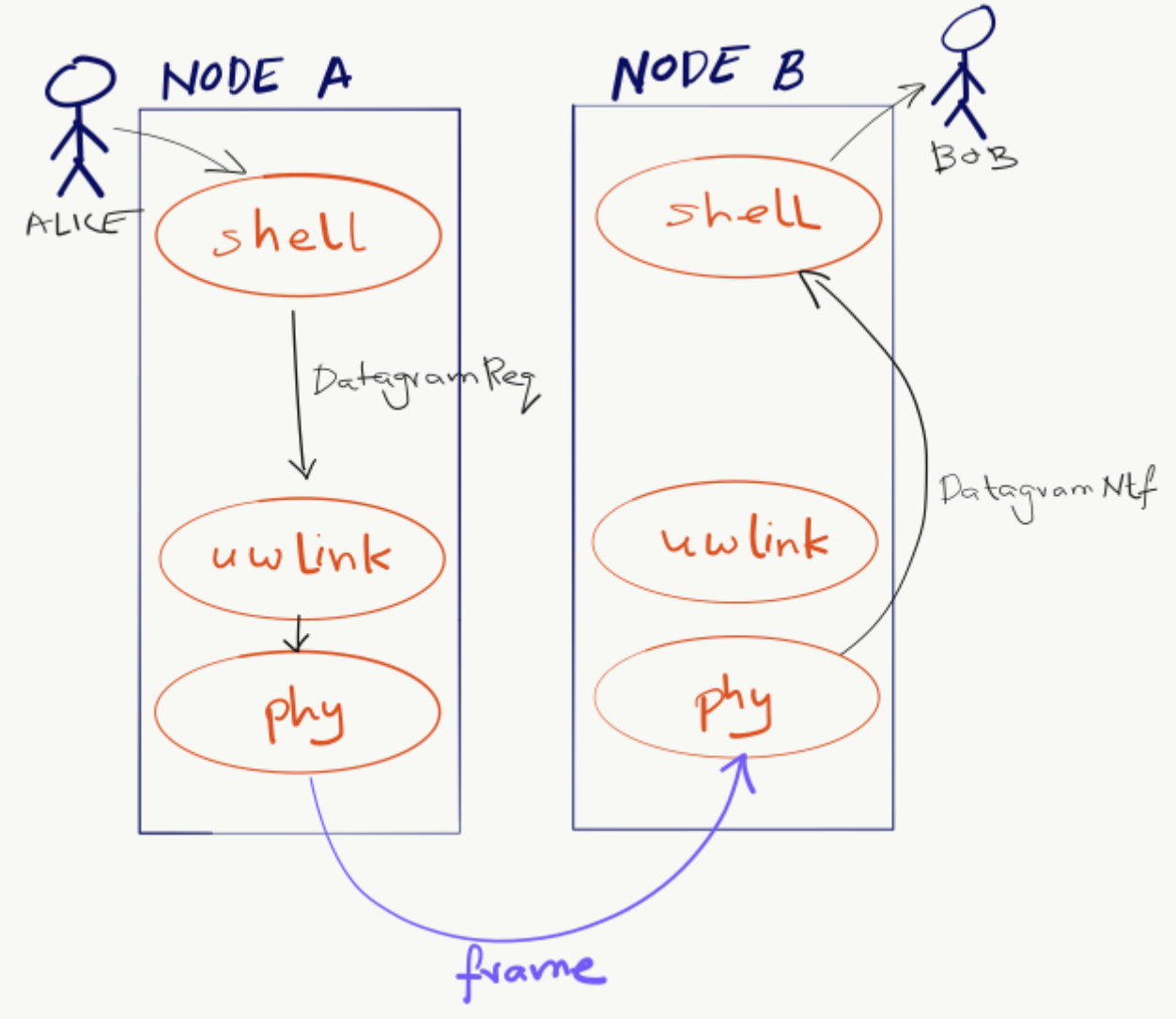


Figure 7. With short-circuit delivery, `uwlink` on node A recognizes the `DatagramReq` to be within the `phy` agent's capability, and no delegates it without adding any headers. On node B, the received frame is directly delivered as a `DatagramNtf` by the `phy` agent, since `uwlink` functionality is not required.

On node B, we should have done this in the first place:

```
> agentsForService(org.arl.unet.Services.DATAGRAM).each { subscribe it }
```

This single-liner in Groovy iterates over the list of agents providing the DATAGRAM service, and subscribes to the topic of each agent in that list.

Agents should use the call `subscribeForService(org.arl.unet.Services.DATAGRAM)` instead. This call subscribes to all agents providing teh DATAGRAM service, but has an added advantage: it also asks the agent to keep track of new agents that are added to the stack later, and subscribes to them if they provide the DATAGRAM service.

13.4. Datagrams and the UnetSocket API

The UnetSocket API also supports delivery of datagrams. Let's try it. On node A:

```
> s = new UnetSocket(this);
> s.send new DatagramReq(to: 31, data: new byte[32])
true
```

On node B, we will see the datagram delivery:

```
uwlink >> DatagramNtf:INFORM[from:232 to:31 (32 bytes)]
```

Note that we did not have to specify an agent or service when making the datagram request via the UnetSocket API. An appropriate agent was automatically selected by the API for us. In this case, the `uwlink` agent was used by the API to deliver the datagram.

Chapter 14. Physical service

`org.arl.unet.Services.PHYSICAL`

Agents offering the PHYSICAL service are most commonly modem drivers and modem simulators. They support messages and parameters that are explained below. PHYSICAL service providers may also provide optional capabilities to send frames triggered at a specified time, or send timestamped frames where the timestamp is embedded in the transmitted frame.

Agents implementing the PHYSICAL service typically directly access the channel, bypassing any MAC protocol that may be in use in the network. It is highly recommended that clients wishing to use the PHYSICAL service consult with the MAC service for advice on when it is safe to access the channel, so as not to adversely affect the network performance.

14.1. Overview

All agents supporting the PHYSICAL service must also support the DATAGRAM service (Chapter 13).

14.1.1. Messages

Agents supporting the PHYSICAL service provide a set of messages to manage frame transmission and reception:

- `TxFrameReq` ⇒ `AGREE` / `REFUSE` / `FAILURE` — transmit a frame
- `TxRawFrameReq` ⇒ `AGREE` / `REFUSE` / `FAILURE` — transmit a frame without headers
- `ClearReq` ⇒ `AGREE` / `REFUSE` / `FAILURE` — cancel all ongoing and pending transmissions
- `RxFrameNtf` — sent to agent's topic when a frame addressed to the node is received, and the agent's `SNOOP` sub-topic when a frame addressed to other nodes is overheard
- `TxFrameNtf` — sent to requestor when a frame is transmitted
- `RxFrameStartNtf` — sent to agent's topic when a frame is detected
- `TxFrameStartNtf` — sent to agent's topic when a frame transmission is started
- `BadFrameNtf` — sent to agent's topic when a bad frame is received
- `CollisionNtf` — sent to agent's topic when a frame is detected (and dropped) while another frame is being received

The `TxFrameReq` class extends a `DatagramReq` to add physical layer options, and the `RxFrameNtf` class extends a `DatagramNtf` to add physical layer metadata.

14.1.2. Parameters

Agents offering the PHYSICAL service support the following parameters:

- `rxEnable` — true if reception is enabled, false otherwise
- `propagationSpeed` — signal propagation speed in m/s

- `time` — current physical layer clock time in microseconds
- `busy` — true if modem is busy transmitting/receiving (carrier sense), false if modem is idle
- `refPowerLevel` — reference source level in dB (re micro-Pascals @ 1m for underwater modems)
- `maxPowerLevel` — maximum allowable transmission power in dB re `refPowerLevel`
- `minPowerLevel` — minimum allowable transmission power in dB re `refPowerLevel`
- `rxSensitivity` — reference receive sensitivity (dB re micro Pascals for underwater modems)

All physical layer timestamps are in microseconds as per the clock provided by the `time` parameter. This clock is generally not synchronized with the platform clock (system time).

In addition to the above parameters, agents also support indexed (frame type) parameters:

- `frameDuration` — frame duration in seconds (maximum duration in case of variable frame length)
- `powerLevel` — transmission power in dB re `refPowerLevel`
- `errorDetection` — number of bytes used for error detection
- `frameLength` — frame length in bytes (maximum length in case of variable frame length)
- `maxFrameLength` — maximum possible frame length in bytes
- `fec` — forward error correction (FEC) code (0 = none/default, otherwise base 1 index from fecList)
- `fecList` — list of available FEC code names (in the order of increasing robustness), may be null if FEC change not supported
- `dataRate` — effective frame data rate (bps)
- `llr` — true to enable log-likelihood ratio reporting in `BadFrameNtf`, false otherwise

Seconds, milliseconds or microseconds?

You'll notice that we use seconds as a unit of time in some places, and milliseconds in others, and microseconds in yet others. While we recognize that this can be confusing at times, there is a good reason for this.

Whenever time or duration can be a `float`, we prefer to use seconds as our unit of time. We also define some Groovy syntactic sugar to allow writing down values in our preferred units, while automatically converting them to seconds. For example: `10.s` → 10.0, `10.ms` → 0.01, and `1.minute` → 60.

Many existing Java and fjåge API calls (e.g. `currentTimeMillis()`, `WakerBehavior()`, `TickerBehavior()`) use the `long` data type for time in milliseconds. Where UnetStack inherits that API, we have no choice but to stick with milliseconds. Do be careful NOT to use values such as `10.ms` there, as these are really values in seconds.

The only time value in microseconds is the PHYSICAL service's `time` parameter, and the corresponding `rxTime`, `recTime` and `txTime` timestamps. This is also inherited by the synchronization time `offset` between node times in the RANGING service.

Two frame types are defined:

- `CONTROL` frame = 1
- `DATA` frame = 2

14.1.3. Capabilities

Agents may support several optional capabilities:

TIMESTAMPED_TX

Agents advertising this capability are able to transmit frames with a transmission timestamp (start of transmission) encapsulated in the frame. This is requested through the `timestamped` flag in the `TxFrameReq` message. In order to do the timestamping, the frame has to be scheduled for transmission after a short delay. This delay is configured via an additional parameter:

- `timestampedTxDelay` — delay in seconds to transmit timestamped frames

TIMED_TX

Agents advertising this capability are able to start transmitting a frame at a specified time (on a best effort basis). The time is given in the `txTime` attribute of the `TxFrameReq` message.

JANUS

If an agent supports the ANEP-87 JANUS standard, it advertises this capability. An additional frame type (indexed parameter set) is defined:

- `JANUS` frame = 3

The JANUS capability also adds one parameter:

- `janus` — true for JANUS frame type, false for all other frame types

It also adds two JANUS-specific messages that are supported:

- `TxJanusFrameReq` ⇒ `AGREE` / `REFUSE` / `FAILURE` — transmit a JANUS frame
- `RxJanusFrameNtf` — sent to agent's topic when a JANUS frame is received

FEC_DECODING

If an agent advertises this capability, it supports an additional request to perform FEC decoding:

- `FecDecodeReq` ⇒ `AGREE` / `REFUSE` / `FAILURE` — attempt FEC decoding a frame, and if successful, send out a `RxFrameNtf`

14.2. CONTROL and DATA channels

The physical layer in UnetStack typically supports 2 logical channels (3 if JANUS is supported). The CONTROL channel provides low-rate, robust communication that allows exchange of small amounts of control information in the network. The DATA channel is a usually a higher rate communication link,

but may require tuning to operate well in various environmental conditions.

The configurable parameters of the CONTROL and DATA channels depend strongly on the device (modem) in use. The Unet simulator provides a simplified physical layer (`HalfDuplexModem`) that captures the essential aspects of the communication using the two channels, exposing only a limited set of parameters. When configuring a real network, you should refer to your modem's manual on advise on how best to set up the physical layer parameters.

Fire up the 2-node network simulation and connect to node A's shell. If you simply type `phy`, you can explore the physical layer parameters for the node:

```
> phy
<<< HalfDuplexModem >>>

[org.arl.unet.DatagramParam]
  MTU = 56

[org.arl.unet.phy.PhysicalParam]
  busy = false
  maxPowerLevel = 0.0
  minPowerLevel = -96.0
  propagationSpeed = 1534.4574
  refPowerLevel = 185.0
  rxEnable = true
  rxSensitivity = -200.0
  time = 9615673299
  timestampedTxDelay = 1.0
```

The `phy.MTU` parameter tells us the maximum amount of user data that can be transmitted in a single frame (56 bytes in this case). This is based on the DATA channel, as we will see shortly, since `DatagramReq` are fulfilled using the DATA channel. The `PhysicalParam` parameters provide us information on whether the channel is busy, transmission power levels supported, receiver sensitivity, and propagation speed of the signal (e.g. speed of sound for underwater modems). The `phy.time` parameter is a microsecond resolution clock that is used to timestamp all physical layer events such as frame transmission, reception, etc.

We can dig deeper into the parameters for the CONTROL and DATA channel separately:

```
> phy[CONTROL]
<<< PHY >>>

[org.arl.unet.DatagramParam]
  MTU = 16

[org.arl.unet.phy.PhysicalChannelParam]
  dataRate = 202.10527
  errorDetection = 1
  fec = 0
  fecList = null
  frameDuration = 0.95
  frameLength = 24
  janus = false
  llr = false
  maxFrameLength = 128
  powerLevel = -10.0

> phy[DATA]
<<< PHY >>>

[org.arl.unet.DatagramParam]
  MTU = 56

[org.arl.unet.phy.PhysicalChannelParam]
  dataRate = 731.4286
  errorDetection = 1
  fec = 0
  fecList = null
  frameDuration = 0.7
  frameLength = 64
  janus = false
  llr = false
  maxFrameLength = 512
  powerLevel = -10.0
```

The values you see above are specific to this simulated network, and will generally be different for different networks, depending on the devices that are being used and the environment that they are deployed in.

Here are a few important parameters to take note of:

- Note that `MTU` for the CONTROL channel is 16 bytes, whereas DATA channel's `MTU` is 56 bytes. CONTROL frames typically carry less data, but are more robust.
- The `frameLength` for the CONTROL and DATA channels are 8 bytes longer than the corresponding `MTU`. The difference is due to header information that the frames carry. The number of bytes taken by the header is device dependent, and also a function of network configuration (e.g. changes in `node.addressSize` may change header size).
- Typically physical layer agents allow setting of the `frameLength` parameter, and the `MTU` parameter is automatically determined based on the necessary headers. The `maxFrameLength` parameter indicates the maximum size of the frame supported.
- The `frameDuration` for the CONTROL channel is about 0.95 seconds, whereas that for the DATA channel is 0.7 seconds. While the CONTROL frames carry less data, they also have lower data rate and so may have comparable duration as the DATA frames.

- The `dataRate` reported by the channel is the effective data rate in bps including the header bits, i.e., it is the frame length in bits divided by the frame duration.
- The `powerLevel` parameter controls the transmission power used by the channel. This value is in dB, with reference to the `phy.refPowerLevel`, and may range between `phy.minPowerLevel` and `phy.maxPowerLevel`.
- The `errorDetection` parameter reports the number of bytes used for error detection CRC (value of 1 indicates that we are using a 8-bit CRC). Some modems will allow you to set this to 2 to switch to 16-bit CRC, if you desire a lower probability of accepting a frame with some bit errors.

14.3. Modem physical layer

In the previous section, we explored several parameters from a simplified simulated physical layer. Next let's look at a real modem. If you are lucky enough to own one with UnetStack on it, you can connect to it's shell now. Otherwise, we can use unet audio SDOAM as our test modem:

```
$ bin/unet audio
Modem web: http://localhost:8080/
```

On the web shell for the modem:

```
> phy
<<< Physical >>>

[org.arl.unet.DatagramParam]
  MTU = 13

[org.arl.unet.phy.PhysicalParam]
  busy = false
  maxPowerLevel = 0.0
  minPowerLevel = -138.0
  propagationSpeed = 1500.0
  refPowerLevel = 0.0
  rxEnable = true
  rxSensitivity = 0.0
  time = 51530438
  timestampedTxDelay = 1000

[org.arl.yoda.ModemParam]
  adcrate = 48000.0
  bbsblk = 6000
  bbscnt = 0
  bpfilter = true
  clockCalib = 1.0
  dacrate = 96000.0
  downconvRatio = 4.0
  fan = false
  fanctl = 45.0
  fullduplex = false
  gain = 0.0
  inhibit = 120
  isc = true
  loopback = false
  model = portaudio
  mute = true
  noise = -62.0
  npulses = 1
  pbsblk = 65536
  pbscnt = 0
  post = null
  poweramp = false
  preamp = true
  pulsedelay = 0
  serial = portaudio
  standby = 15
  upconvRatio = 8.0
  vendor = Subnero
  voltage = 0.0
  wakeupdelay = 400
  wakeuplen = 8000
```

For brevity, we have omitted the baseband service and scheduler service parameters in the listing above. Even then, there are many parameters that allow you to configure the SDOAM. We cannot cover each parameter in detail here, but we encourage you to explore the help pages for the parameters by simply typing `help phy.` followed by the parameter name.

Further, let's look at the indexed parameters for the CONTROL channel:

```
> phy[CONTROL]
<<< PHY >>>

[org.arl.unet.DatagramParam]
  MTU = 13

[org.arl.unet.phy.PhysicalChannelParam]
  dataRate = 70.588234
  errorDetection = true
  fec = 1
  fecList = [ICONV2]
  frameDuration = 2.04
  frameLength = 18
  janus = false
  llr = false
  maxFrameLength = 396
  powerLevel = -10.0

[org.arl.yoda.FhbfskParam]
  chiplen = 1
  fmin = 9520.0
  fstep = 160.0
  hops = 13
  scrambler = 0
  sync = true
  tukey = true

[org.arl.yoda.ModemChannelParam]
  basebandExtra = 0
  basebandRx = false
  modulation = fhbfsk
  preamble = (480 samples)
  test = false
  threshold = 0.25
  valid = true
```

Again, we cannot cover all the parameters in detail here, but will draw your attention to a few important ones. You see that the `modulation` for the CONTROL channel is set to `'fhbfsk'` (frequency-hopping binary frequency shift keying). Depending on your modem, different modulations may be supported. Once a modulation scheme is chosen, you see additional modulation-dependent parameters. In this case, these are the `org.arl.yoda.FhbfskParam` parameters such as `fmin`, `fstep`, `hops`, `chiplen`, `tukey`, etc. These parameters allow you to control the modulation's frequency band, number of hops, chip duration, windowing, etc.

If you change modulation parameters, you have to remember to do it on all your modems in the network. Otherwise they will be speaking different *languages*, and they won't be able to understand each other. Not all combination of modulation parameters are valid. The `valid` parameter tells us if the current setting is valid or not. If the setting is invalid, all transmission requests will be refused.

The `preamble` parameter determines a detection preamble that is transmitted before each frame. This is used by the receiving modem to determine the start of a frame. The `threshold` parameter controls the detection probability and false alarm rate for frame detection. A lower threshold will improve detection probability, but increase false alarm rate.

If the `test` flag is set on the transmission and reception modems, each transmit frame is filled with known test data. This allows the receiving modem to compute the bit error rate (BER), even when the frame has too many errors for FEC to be able to correct.

14.4. Transmitting & receiving using Unet audio

If you have two computers with speakers and microphones, you could run unet audio on both, and communicate between the two. If you happen to have only one computer handy, do not worry — we can get one unet audio instance to transmit and receive at the same time. This is full-duplex communication!

Real modems typically cannot do full-duplex communication because the weak incoming signals are masked by clutter from the strong outgoing signal. However, by adjusting the volume of your computer carefully, you can easily do full-duplex communication on your unet audio SDOAM.

On unet audio shell, enable full-duplex operation and try a transmission (you should be able to hear it from your computer speaker!). Your output might not look exactly the same, but let's go over all the notifications we got and see if we can understand all of them:

```
> phy.fullduplex = true
true
> subscribe phy
> phy << new TxFrameReq()
AGREE
phy >> TxFrameStartNtf:INFORM[type:CONTROL txTime:79322682]                ①
phy >> RxFrameStartNtf:INFORM[type:CONTROL rxTime:79309353 detector:0.87]  ②
phy >> RxFrameStartNtf:INFORM[type:DATA rxTime:80659519 detector:0.26]     ③
phy >> TxFrameNtf:INFORM[type:CONTROL txTime:79310432]                     ④
phy >> RxFrameNtf:INFORM[type:CONTROL from:1 rxTime:79309353 rssi:-29.3]   ⑤
phy >> BadFrameNtf:INFORM[type:DATA rxTime:80659519 rssi:-38.5 (18 bytes)] ⑥
```

① Transmission of our requested CONTROL frame has started.

② Our frame being transmitted was detected as a CONTROL frame, and reception has started.

③ Our frame being transmitted was wrongly detected (false alarm) as a DATA frame.

④ Transmission of our frame was completed.

⑤ Reception of the frame was completed, and successful.

⑥ The wrongly detected frame resulted in data that did not satisfy CRC, and hence reported as a bad frame.

To get rid of the false alarm on the DATA channel, we could either increase the detection threshold or turn off the detector completely (`phy[DATA].threshold = 0`). For now, we'll do the latter. Let's also turn on the `phy[CONTROL].test` flag so that we can measure communication performance in terms of BER. To measure BER before error correction, we also need to turn off `phy[CONTROL].fec`:

```
> phy[DATA].threshold = 0
0
> phy[CONTROL].test = true
true
> phy[CONTROL].fec = 0
0
```

Now we can make 10 transmissions, 2 seconds apart, and watch the BER of the received frames:

```
> 10.times { phy << new TxFrameReq(); delay(2000); }
phy >> TxFrameNtf:INFORM[type:CONTROL txTime:204359766]
phy >> RxFrameNtf:INFORM[type:CONTROL rxTime:204385187 rssi:-28.9 cfo:0.0 ber:0/144 (18 bytes)]
phy >> TxFrameNtf:INFORM[type:CONTROL txTime:205578432]
phy >> RxFrameNtf:INFORM[type:CONTROL rxTime:205603853 rssi:-28.4 cfo:0.0 ber:0/144 (18 bytes)]
phy >> TxFrameNtf:INFORM[type:CONTROL txTime:207567766]
phy >> RxFrameNtf:INFORM[type:CONTROL rxTime:207589186 rssi:-28.5 cfo:0.0 ber:0/144 (18 bytes)]
phy >> TxFrameNtf:INFORM[type:CONTROL txTime:209583766]
phy >> RxFrameNtf:INFORM[type:CONTROL rxTime:209609187 rssi:-28.2 cfo:0.0 ber:0/144 (18 bytes)]
phy >> TxFrameNtf:INFORM[type:CONTROL txTime:211573099]
phy >> RxFrameNtf:INFORM[type:CONTROL rxTime:211594519 rssi:-28.3 cfo:0.0 ber:0/144 (18 bytes)]
phy >> TxFrameNtf:INFORM[type:CONTROL txTime:213589099]
phy >> RxFrameNtf:INFORM[type:CONTROL rxTime:213614520 rssi:-28.1 cfo:0.0 ber:0/144 (18 bytes)]
phy >> TxFrameNtf:INFORM[type:CONTROL txTime:215578432]
phy >> RxFrameNtf:INFORM[type:CONTROL rxTime:215599853 rssi:-28.5 cfo:0.0 ber:0/144 (18 bytes)]
phy >> TxFrameNtf:INFORM[type:CONTROL txTime:217594432]
phy >> RxFrameNtf:INFORM[type:CONTROL rxTime:217619853 rssi:-28.2 cfo:0.0 ber:0/144 (18 bytes)]
phy >> TxFrameNtf:INFORM[type:CONTROL txTime:219583766]
phy >> RxFrameNtf:INFORM[type:CONTROL rxTime:219605186 rssi:-28.0 cfo:0.0 ber:0/144 (18 bytes)]
phy >> TxFrameNtf:INFORM[type:CONTROL txTime:221599766]
phy >> RxFrameNtf:INFORM[type:CONTROL rxTime:221625187 rssi:-27.7 cfo:0.0 ber:0/144 (18 bytes)]
```

For brevity, we have omitted the `TxFrameStartNtf` and `RxFrameStartNtf` messages. We see that no bits were in error, out of 144 transmitted bits. We had perfect communication, even without FEC! This is not surprising since the speaker and microphone are very close (and hence good signal-to-noise ratio), but real channels are rarely so forgiving. You can try this between 2 computers, and things may not be as rosy.

Feel free to play around with the parameters of the modulation scheme and try transmissions to get a feel for how the parameters affect communication performance. Since your transmission and reception modems are the same, you only need to set the parameters once! In real life, you'll need to set the same parameters on all modems in your network.

Remember to turn off the `phy[CONTROL].test` flag before trying any data transfer. While the flag is on, no user data can be carried by the transmitted frames.

14.5. Timed and timestamped transmissions

To explore timed and timestamped transmissions, let's go back to our 2-node network simulation. On the shell for node A:

```
> phy << new CapabilityReq()
CapabilityListRsp:INFORM[TIMESTAMPED_TX,TIMED_BBREC,TIMED_BBTX,TIMED_TX]
```

We see that the phy agent supports the TIMESTAMPED_TX and TIMED_TX optional capabilities. Let us try them out. On node B:

```
> subscribe phy
```

Going back to node A, send a timestamped frame:

```
> phy << new TxFrameReq(timestamped: true)
AGREE
phy >> TxFrameNtf:INFORM[type:CONTROL txTime:2489196375]
```

We see that the frame was transmitted at time 2489196375 (when you try this, the time will of course be different). You should see the RxFrameNtf for this frame on node B:

```
phy >> RxFrameStartNtf:INFORM[type:CONTROL rxTime:687419054]
phy >> RxFrameNtf:INFORM[type:CONTROL from:232 rxTime:687419054 txTime:2489196375]
```

Note that the RxFrameNtf now has an additional txTime field that's populated, and the timestamp in there is the same as the txTime on node A's TxFrameNtf. The frame was timestamped before transmission, and transmitted at exactly the intended time.

Timestamps take up bits in the transmitted frame. Your effective MTU for frames with timestamps is 6 bytes less than the advertised MTU.

Do bear in mind that the phy.time clocks on node A and B may not be synchronized. So timestamps from one node cannot be directly compared with timestamps on another node. In the above example, the rxTime was 687,419,054 microseconds, whereas the txTime was 2,489,196,375 microseconds. This does not mean that the frame was received before it was transmitted! It's just that node A and B have an offset between their clocks.

Sometimes you may not need to transmit a timestamped frame, but you do want the frame to be transmitted at a specified time. On node A:

```
> t = phy.time + 5000000; println(t); phy << new TxFrameReq(txTime: t) ①
3174864375                                                              ②
AGREE
phy >> TxFrameNtf:INFORM[type:CONTROL txTime:3174864375]                ③
```

① t is the current time + 5 seconds. We ask for a frame to be transmitted at time t.

② The value of time t is printed immediately (due to the println(t)).

③ The TxFrameNtf message will appear after a few seconds, once the transmission is made. Note that the actual txTime when the transmission occurred matches with our requested value t.

If you check node B's shell, you'll find the corresponding RxFrameNtf, but it will not have a txTime field, as the frame transmitted was not timestamped.

The transmission time is honored on a *best effort* basis, which means that there could be a small difference between the requested time and the actual transmit time.

14.6. Snooping frames meant for other nodes

If you're familiar with Ethernet network interface cards, you may have come across *promiscuous mode*. In this mode, the network card receives all packets that it hears, not just the ones that are addressed to the node. Agents providing the PHYSICAL service essentially do this continuously, but they send the notifications for frames intended for other nodes on a special sub-topic called SNOOP.

With the 2-node network simulation, let's first only subscribe to the `phy` agent's topic on node B:

```
> subscribe phy
```

From node A, transmit a frame to node B and to node C (node C does not exist in this network):

```
> phy << new TxFrameReq(to: host('B'))
AGREE
phy >> TxFrameNtf:INFORM[type:CONTROL txTime:4622534375]
> phy << new TxFrameReq(to: host('C'))
AGREE
phy >> TxFrameNtf:INFORM[type:CONTROL txTime:4623823375]
```

On node B, you'll find that it receives the `RxFrameStartNtf` for both transmissions, but only the `RxFrameNtf` for the transmission addressed to node B:

```
phy >> RxFrameStartNtf:INFORM[type:CONTROL rxTime:2820757054]
phy >> RxFrameNtf:INFORM[type:CONTROL from:232 to:31 rxTime:2820757054]
phy >> RxFrameStartNtf:INFORM[type:CONTROL rxTime:2822046054]
```

The `RxFrameStartNtf` is sent when a frame is detected. At that point in time, the agent has no idea whom the frame is intended for, because the frame contents have not yet arrived. Only when the frame is received and decoded does the agent know the destination address. Seeing that the second frame was intended for node C, node B does not report a `RxFrameNtf` for it.

If you were interested in snooping conversations between other nodes, you could subscribe to the SNOOP topic on node B:

```
> subscribe topic(phy, org.arl.unet.phy.Physical.SNOOP)
```

Now try transmitting another frame from node A to node C. On node A:

```
> phy << new TxFrameReq(to: host('C'))
AGREE
phy >> TxFrameNtf:INFORM[type:CONTROL txTime:4899843375]
```

Now you'll see on node B that the corresponding `RxFrameNtf` is received:

```
phy >> RxFrameStartNtf:INFORM[type:CONTROL rxTime:3098066054]
phy >> RxFrameNtf:INFORM[type:CONTROL from:232 to:74 rxTime:3098066054]
```

The `to` address of 74 corresponds to `host('C')`, but the frame is available for agents on node B through the SNOOP topic.

Chapter 15. Baseband service

`org.arl.unet.Services.BASEBAND`

Software-defined modems often allow developers to transmit and record arbitrary waveforms. This functionality is encapsulated in the baseband service of UnetStack.

Agents implementing the baseband service typically directly access the channel, bypassing any MAC protocol that may be in use in the network. It is highly recommended that clients wishing to use the baseband service for transmitting arbitrary waveforms consult with the MAC service for advice on when it is safe to access the channel, so as not to adversely affect the network performance.

15.1. Overview

Agents offering the baseband service are most commonly modem drivers (and simulators). They support a set of messages and parameters that are explained below. Baseband service providers may also provide optional capabilities to send or record signals at a specified time, or based on premable detection.

15.1.1. Messages

Agents supporting the baseband service provide messages for arbitrary signal transmission and recording:

- `TxBasebandSignalReq` ⇒ `AGREE` / `REFUSE` / `FAILURE` — transmit a signal
- `RecordBasebandSignalReq` ⇒ `AGREE` / `REFUSE` / `FAILURE` — record a signal
- `RxBasebandSignalNtf` — signal recording sent to requestor, or to agent's topic if the recording was not specifically requested

During signal transmission, an agent implementing the baseband service sends out `TxFrameStartNtf` and `TxFrameNtf`, as described in the PHYSICAL service (Chapter 14). Similarly, if recording is triggered on a preamble detection, the agent sends out a `RxFrameStartNtf` as described in the PHYSICAL service.

Detection preambles are often added to transmitted signals for the receiving modem to identify the incoming signals. The receiving modem can capture the signal when it detects the preamble, and then send a `RxBasebandSignalNtf`. If a modem supports multiple preambles, the `TxBasebandSignalReq` can specify the `preamble` to be used. Setting the `preamble` to 0 results in a signal transmission without a preamble. Such a transmission will ordinarily not be received by any modem, unless it is recorded by an explicit `RecordBasebandSignalReq` at the appropriate time.

15.1.2. Parameters

Agents offering the baseband service support the following parameter:

- `carrierFrequency` — default carrier frequency for baseband signals (Hz)
- `basebandRate` — default baseband sampling rate for baseband signals (samples/s)

- `maxPreambleID` — maximum preamble identifier supported
- `maxSignalLength` — maximum baseband signal length (in samples) for transmission/reception
- `signalPowerLevel` — signal transmission power level in dB re `refPowerLevel` (`refPowerLevel` is specified in the PHYSICAL service)

15.1.3. Capabilities

Agents may support several optional capabilities:

TIMED_BBTX

Agents advertising this capability are able to transmit signals at specified time (on a best effort basis). The time is given in the `txTime` attribute of the `TxBasebandSignalReq` message.

TIMED_BBREC

Agents advertising this capability are able to record signals at specified time (on a best effort basis). The time is given in the `recTime` attribute of the `RecordBasebandSignalReq` message.

15.2. Baseband and passband signals

Communication systems usually represent signals in a complex baseband representation, as this allows them to be sampled at a lower sampling rate than real passband signals. Passband signals have to be sampled at more than twice the highest frequency (Nyquist criterion). Baseband signals need to be sampled at more than twice the bandwidth. Since the bandwidth is typically much lesser than the carrier frequency, the baseband representation is usually more economical than the passband representation.

While the baseband service is aimed at signals represented in the complex baseband representation, it also supports signals represented as real passband samples. Such signals are identified by setting the `fc` (carrier frequency) field of the `TxBasebandSignalReq` or `RxBasebandSignalNtf` to 0. Modems offering the baseband service may optionally support passband signal transmission and recording.

Since Java and Groovy do not support complex numbers natively, the complex baseband signals are represented by an array of floats with alternate samples from the in-phase (real part) and quadrature (imaginary part) channels. In languages that support complex numbers (e.g. Python and Julia), the signals are represented as arrays (or lists) of complex numbers.

If all this seems to be confusing, don't worry, it'll become clear as we go through examples shortly.

15.3. Transmitting and recording arbitrary signals

In Section 2.7, you already saw how to transmit and record arbitrary signals. We then used the convenience functions `bbtx` and `bbrec` for simplicity. In this chapter, we will do the same thing by sending the `TxBasebandSignalReq` and `RecordBasebandSignalReq` messages instead. As you'll see, these messages provide you greater control, and can also be sent via the UnetSocket API or a fjåge gateway from external applications.

Fire up unet audio to try out the examples here:

```
$ bin/unet audio
Modem web: http://localhost:8080/
```

On the shell for the unet audio SDOAM, check which agents provide the baseband service:

```
> agentsForService(org.arl.unet.Services.BASEBAND)
[phy]
```

We can now direct all our requests to the `phy` agent. Let's check the baseband parameters of the `phy` agent (we omit other parameters here for brevity):

```
> phy
<<< Physical >>>

[org.arl.unet.bb.BasebandParam]
  basebandRate = 12000.0
  carrierFrequency = 12000.0
  maxPreambleID = 4
  maxSignalLength = 2147483647
  signalPowerLevel = -10.0
```

We see that the unet audio SDOAM operates at a carrier frequency of 12 kHz and a bandband sampling rate of 12 kSa/s. Let's create a DC signal of length 12000 complex baseband samples (24000 floats) and transmit it. A DC signal of length 12000 complex samples with a carrier frequency of 12 kHz is a sinusoidal 12 kHz signal for 1 second.

```
> s = [1,0]*12000                ①
[1, 0, 1, 0, 1, 0, 1, 0, 1, 0, 1 <<snip>> 0, 1, 0, 1, 0, 1, 0, 1, 0, 1, 0]
> s.size()
24000
> phy << new TxBasebandSignalReq(signal: s)
AGREE
phy >> TxFrameNtf:INFORM[txTime:11401231]
```

① In Groovy, we can repeat a list using the "*" operator. The list [1,0] represents a complex number 1+0j. Repeating it 12000 times gets us a 1 second long DC signal.

You should hear the sound from your computer speaker.

You can generate other frequency signals using the `cw()` (continuous wave) function available in the shell. You can also save and load signals from text files using the `save` and `load` commands. For information on all these commands/functions, simply type `help cw`, `help save` or `help load`.

Unet audio supports transmission of passband signals as well. Let us create a half second 2000 kHz passband signal and transmit it:

```
> s = cw(2000, 0.5, 0)                              ①
> s.size()
48000                                               ②
> phy << new TxBasebandSignalReq(signal: s, fc: 0) ③
AGREE
phy >> TxFrameNtf:INFORM[txTime:414013271]
```

① The `cw()` function enables us to create baseband or passband continuous wave signals. The third parameter is the carrier frequency. Setting that to 0 creates a baseband signal.

② Notice that our signal is 48000 floats for 0.5 seconds. Compare that with the previous DC signal, which was 24000 floats for 1 second.

③ The `fc` field is set to 0 to tell `phy` that the `signal` is given in passband.

Next, let's request a recording of 12000 samples (1 second duration):

```
> phy << new RecordBasebandSignalReq(recLength: 12000)
AGREE
phy >> RxBasebandSignalNtf:INFORM[adc:1 rxTime:11780353 rssi:-79.1 fc:12000.0 fs:12000.0 (12000 baseband
samples)]
> ntf.signal                        ①
[8.611694E-5, 5.8899976E-5, 1.01 <<snip>> E-6, -9.148392E-6, 3.5340495E-6]
```

① The `ntf` variable holds the last received notification, which in this case is the `RxBasebandSignalNtf`. The `signal` field contains the complex baseband recording.

You can also ask for recordings to begin at a specified time:

```
> t = phy.time + 5000000; println(t); phy << new RecordBasebandSignalReq(recLength: 12000, recTime: t)
855949105
AGREE
phy >> RxBasebandSignalNtf:INFORM[adc:1 rxTime:855949105 rssi:-90.3 fc:12000.0 fs:12000.0 (12000 baseband
samples)]
```

You'd have noticed the 6 second delay (5 seconds to begin recording, 1 more second to finish the recording) before the recording notification.

Interestingly, you can also request recordings in the past! Many modems have a short buffer, allowing recording in the recent past. Go too far in the past and the modem will refuse your request!

```
> t = phy.time - 5000000; println(t); phy << new RecordBasebandSignalReq(recLength: 12000, recTime: t)
1186471772
AGREE
phy >> RxBasebandSignalNtf:INFORM[adc:1 rxTime:1186471772 rssi:-74.6 fc:12000.0 fs:12000.0 (12000 baseband
samples)]
> t = phy.time - 60000000; println(t); phy << new RecordBasebandSignalReq(recLength: 12000, recTime: t)
1204946438
REFUSE: Bad start time
```

Specifying a negative `recTime` is understood by the baseband service provider as a relative time. So we can simpify our request to record 5 seconds in the past:

```
> phy << new RecordBasebandSignalReq(recLength: 12000, recTime: -5000000)
AGREE
phy >> RxBasebandSignalNtf:INFORM[adc:1 rxTime:1361359020 rssi:-72.9 fc:12000.0 fs:12000.0 (12000 baseband
samples)]
```

15.4. Transmitting and detecting preambles

Each logical channel (CONTROL, DATA, etc.) is associated with a detection preamble. Detectors in a modem monitor incoming signals, and trigger when the preamble is detected.

We can transmit a preamble easily:

```
> phy << new TxBasebandSignalReq(preamble: 1)
AGREE
phy >> TxFrameNtf:INFORM[txTime:5470777099]
```

Here, we did not specify a signal to transmit, so only the preamble was transmitted. You should have heard the preamble as a short chirp from your computer speaker. If we had specified a signal, the preamble would have been followed by the signal.

If you had another unet audio SDOAM running nearby, it would have heard the preamble and detected a CONTROL frame. It would have tried to decode the frame, but failed, as we didn't actually transmit anything after the preamble. So you'd have seen a `RxFrameStartNtf` followed by a `BadFrameNtf` if you had subscribed to `phy` topic on that modem.

If you don't have access to another computer to run unet audio on, we can easily demonstrate the above behavior with a single unet audio SDOAM by simply enabling the full-duplex mode (and hence using the same computer for transmission and reception simultaneously), as we did in Chapter 14:

```
> subscribe phy
> phy.fullduplex = true
true
> phy << new TxBasebandSignalReq(preamble:1)
AGREE
phy >> TxFrameStartNtf:INFORM[txTime:5809832016 txDuration:40416]
phy >> TxFrameNtf:INFORM[txTime:5809859766]
phy >> RxFrameStartNtf:INFORM[type:CONTROL rxTime:5809825603 rxDuration:2740000 detector:0.9]
phy >> BadFrameNtf:INFORM[type:CONTROL rxTime:5809825603 rssi:-55.6 (18 bytes)]
```

Preambles 1 and 2 are used by the CONTROL and DATA channel respectively. It's better not to mess with these, but instead use preamble 3, which is left for the user to configure in unet audio. By default, detection of preamble 3 is disabled. You can enable it by setting the detection threshold `phy[3].threshold` parameter. Let's try it:

```
> phy[3].threshold = 0.25
0.25
> phy << new TxBasebandSignalReq(preamble: 3)
AGREE
phy >> TxFrameStartNtf:INFORM[txTime:6011688016 txDuration:170916]
phy >> TxFrameNtf:INFORM[txTime:6011686599]
phy >> RxFrameStartNtf:INFORM[type:#3 rxTime:6011700270 rxDuration:170500 detector:0.73]
```

We see the RxFrameStartNtf of type #3 indicating that preamble 3 was detected. Since phy[3] is not associated with any modulation scheme, the modem did not generate a BadFrameNtf as it did with preamble 1.

Preambles 1, 2 and 3 are preconfigured on the unet audio SDOAM to be short signals with good autocorrelation properties. You can change these, if you wish, by setting the preamble indexed parameter (type help phy[].preamble for details).

In applications such as sonar or ranging, we may only be interested in the detecting the timing of a known signal. In that case, the RxFrameStartNtf is sufficient for us. But in some applications, we may wish to capture the signal once detected. That can be easily achieved in unet audio by setting the basebandRx parameter.

The basebandRx and basebandExtra parameters are provided by the unet audio SDOAM, and work closely with the baseband service. These are not currently part of the baseband service specifications, but are under consideration for adoption as part of the service. Most modems that currently support the baseband service also support these parameters.

If you enable basebandRx, a recording will be triggered every time the preamble is detected:

```
> phy[3].basebandRx = true
true
> phy << new TxBasebandSignalReq(preamble: 3)
AGREE
phy >> TxFrameStartNtf:INFORM[txTime:6992613349 txDuration:170916]
phy >> TxFrameNtf:INFORM[txTime:6992598599]
phy >> RxFrameStartNtf:INFORM[type:#3 rxTime:6992616269 rxDuration:170500 detector:0.78]
phy >> RxBasebandSignalNtf:INFORM[adc:1 rxTime:6992616269 rssi:-22.0 preamble:3 fc:12000.0 fs:12000.0
(2046 baseband samples)]
```

The RxBasebandSignalNtf notified us of the recorded signal (containing just the detected preamble). If we wanted a longer recording after the preamble, we can ask for that using the basebandExtra parameter, specifying the length of the recording (in samples) beyond the preamble:

```
> phy[3].basebandExtra = 1200     ①
1200
> phy << new TxBasebandSignalReq(preamble: 3)
AGREE
phy >> TxFrameStartNtf:INFORM[txTime:7143093349 txDuration:170916]
phy >> TxFrameNtf:INFORM[txTime:7143062599]
phy >> RxFrameStartNtf:INFORM[type:#3 rxTime:7143081603 rxDuration:1170500 detector:0.78]
phy >> RxBasebandSignalNtf:INFORM[adc:1 rxTime:7143081603 rssi:-36.7 preamble:3 fc:12000.0 fs:12000.0
(3246 baseband samples)]
```

① We are requesting 100 ms recording beyond the end of the preamble.

You can see that the recording is much longer now.

If you cross-correlate this recording with the preamble you transmitted, you'd get an estimate of the impulse response of the channel between your computer speaker and microphone! You can easily obtain the complex baseband representation of preamble #3 that you have been transmitting (`phy[3].preamble.signal`), if you wanted to try doing this.

15.5. Baseband signal monitor

During the development of signal processing algorithms, one often wants to simply record received signals in the modem for postprocessing. For this, you could write a script to listen for `RxBasebandSignalNtf` messages from `phy` agent's topic, and store them in a file. Since this requirement is common, UnetStack already provides an agent which does exactly this. The agent is called `BasebandSignalMonitor` or `bbmon` for short.

The `bbmon` agent is already loaded when you run unet audio. However, by default, it is disabled. It's easy to enable it:

```
> bbmon.enable = true
true
```

Now, every `RxBasebandSignalNtf` that is sent to `phy` agent's topic will be recorded in a `signal-0.txt` file in the `logs` folder.

```
> logs                                              ①
signals-0.txt [0 bytes]                             ②
results.txt [39 bytes]
phy-log-0.txt [687 bytes]
log-0.txt [4 kB]
> phy << new TxBasebandSignalReq(preamble: 3)       ③
AGREE
phy >> TxFrameStartNtf:INFORM[txTime:102528016 txDuration:170916]
phy >> TxFrameNtf:INFORM[txTime:102513266]
phy >> RxFrameStartNtf:INFORM[type:#3 rxTime:102531520 rxDuration:270500 detector:0.74]
phy >> RxBasebandSignalNtf:INFORM[adc:1 rxTime:102531520 rssi:-23.6 preamble:3 fc:12000.0 fs:12000.0 (3246
baseband samples)]
> logs
signals-0.txt [34 kB]                               ④
results.txt [39 bytes]
phy-log-0.txt [687 bytes]
log-0.txt [5 kB]
```

① Check the logs folder.

② We have a `signals-0.txt` file with no data.

③ Transmit preamble #3. This will trigger a recording, based on the `phy[3]` configuration from the previous section.

④ Now the `signals-0.txt` file has grown to 34 kB. It contains the signal that was just recorded.

As you record more signals, they are appended to the same file (with delineating metadata for each signal). If you restart unet audio, this file will be renumbered to `signals-1.txt`, as the logs are rotated.

The name of the signals file and number of files kept through log rotation is configured when the `bbmon` agent is loaded. This happens in the `etc/setup.groovy` file in your unet audio installation, and you can change it, if you like.

The signals file stores the signals in a base64 encoded format. The Python package `arlpy.unet` allows you to read this file and work with the signals in it:

```
$ pip install arlpy          ①
$ ipython
Python 3.6.8 |Anaconda custom (64-bit)| (default, Dec 29 2018, 19:04:46)
Type 'copyright', 'credits' or 'license' for more information
IPython 6.2.1 -- An enhanced Interactive Python. Type '?' for help.

In [1]: from arlpy import unet
In [2]: s = unet.get_signals('logs/signals-0.txt')
In [3]: s                    ②
Out[3]:
           time    rxtime  adc  channels  fc ...    len  preamble  rssi            filename  lno
0  1567961114848  75224853    1         1   0 ...   3246         3 -23.6  logs/signals-0.txt    1

[1 rows x 12 columns]

In [4]: x = unet.get_signal(s, 0)
In [5]: x.shape              ③
Out[5]: (3246,)
In [6]: x
Out[6]:
array([ 9.50995535e-02-3.77136953e-02j,  1.30487725e-01-1.90211199e-02j,
        1.27376720e-01+1.91459619e-02j, ...,
        8.61445224e-05+2.21590763e-05j, -2.69901575e-05-3.34111392e-05j,
        3.39479702e-05-1.82653162e-06j])
```

① Install the `arlpy` pacakge. You need to do this only if you don't already have it installed. The output of this command is omitted here.

② `s` is now a pandas table with an index of all signals available in `signals-0.txt`.

③ `x` is now signal #0 (first signal) from the `signals-0.txt` file.

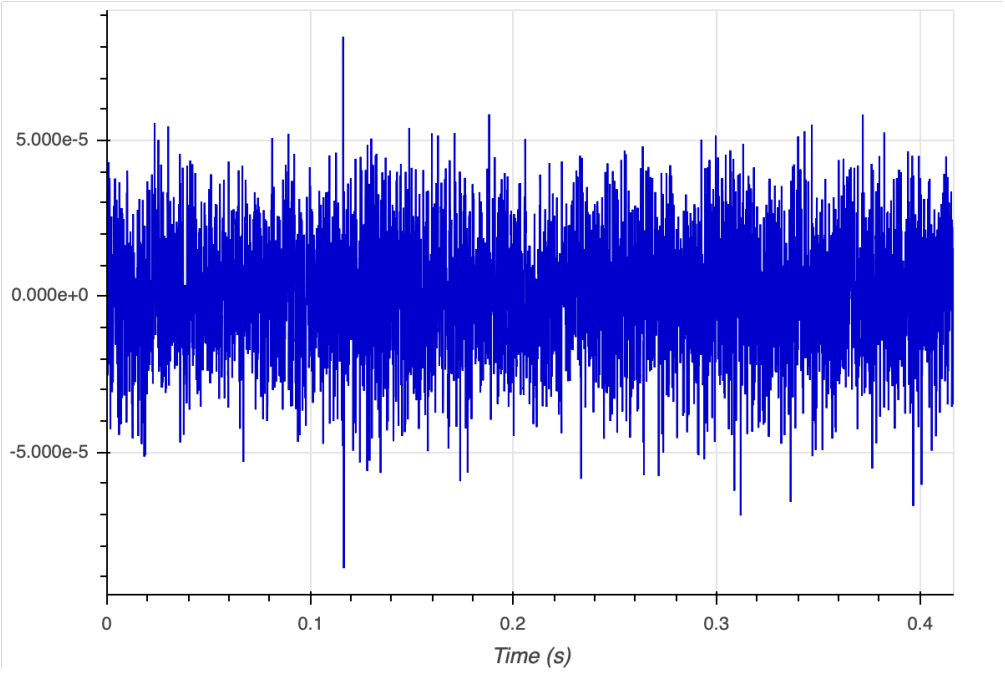
15.6. Transmitting and receiving waveforms directly from Python

In the previous section, we showed you how to record signals for postprocessing. This is great if you postprocessing is what you desire, but sometimes it is important to access the functionality in real time from Python. This is very useful while debugging new signal processing algorithms, since tools such as Jupyter notebooks and libraries such as `numpy`, `scipy`, `pandas`, `arlpy`, and many others have made Python the preferred platform for a lot of scientific computation.

Let's try it!

You had already installed the Python package `unetpy` in Section 2.5. We'll be using it now, so in case you don't have it installed, now is a good time to install it. Start a Jupyter new notebook with Python 3 and connect to your unet audio instance:

```
In[1]:   from unetpy import *
         import arlpy.plot as plt

In[2]:   # connect to the unet audio SDOAM
         sock = UnetSocket('localhost', 1100)
         gw = sock.getGateway()

In[3]:   # lookup the agent providing baseband service
         bb = gw.agentForService(Services.BASEBAND)
         bb.name
Out[3]:  'phy'

In[4]:   # transmit preamble 3 -- you should be able to hear it
         bb << TxBasebandSignalReq(preamble=3)
Out[4]:  AGREE

In[5]:   # discard old notifications to get ready for a recording
         gw.flush()

In[6]:   # request a recording
         bb << RecordBasebandSignalReq()
Out[6]:  AGREE

In[7]:   # obtain the recording notification and check that it's of the correct type
         ntf = gw.receive(timeout=5000)
         ntf
Out[7]:  RxBasebandSignalNtf:INFORM[rxTime:203329687 rssi:-68.847565 adc:1 fc:12000.0 fs:12000.0 channels
:1 preamble:0 (65536 samples)]

In[8]:   # close the connection
         sock.close()

In[9]:  len(ntf.signal)
Out[9]: 65536

In[10]:  # plot the first 10000 baseband samples (real/in-phase components only)
         plt.plot(ntf.signal[:10000].real, fs=ntf.fs)
Out[10]:
```



Of course you could do the same thing with Julia or other languages, if you wish, with obvious minor changes to the syntax!

Chapter 16. Ranging and synchronization

`org.arl.unet.Services.RANGING`

It is common to use underwater acoustic modems for range estimation, as the travel time of acoustic signals can easily be measured. In Section 2.3, we saw that we can use the `range` command to estimate range between nodes. This command uses the RANGING service described below.

Ranging is closely related to time synchronization, since travel time measurement between two nodes requires some sort of synchronization between the nodes. If the nodes are synchronized, one-way travel time (OWTT) can be directly measured and used to estimate range. If the nodes are not synchronized, two-way travel time (TWTT) can be used to measure range and synchronize the nodes simultaneously. The RANGING service supports both modes of ranging, and manages synchronization information between nodes.

16.1. Overview

The RANGING service provides messages and parameters to support OWTT and TWTT ranging, and to manage synchronization information between the nodes.

16.1.1. Messages

The following messages are defined by the RANGING service:

- `RangeReq` ⇒ `AGREE` / `REFUSE` / `FAILURE` — measure range to peer node via OWTT or TWTT
- `BeaconReq` ⇒ `AGREE` / `REFUSE` / `FAILURE` — transmit beacon message for OWTT
- `SyncInfoReq` ⇒ `SyncInfoRsp` / `REFUSE` / `FAILURE` — get synchronization information for peer node
- `ClearSyncReq` ⇒ `AGREE` / `REFUSE` / `FAILURE` — clear synchronization information for peer node
- `RangeNtf` — sent to agent's topic when range information for peer node becomes available
- `BadRangeNtf` — sent to agent's topic when invalid range information for peer node indicates potentially outdated synchronization with that node

The use of these messages will become clearer through examples below.

16.1.2. Parameters

A few parameters control the behavior of the RANGING service provider:

- `channel` — channel (DATA/CONTROL) to use for ranging
- `lifetime` — lifetime or validity for synchronization information (seconds)
- `minRange` — minimum valid range (m)
- `maxRange` — maximum valid range (m)
- `maxBadRangeCnt` — number of `BadRangeNtf` for peer node to discard synchronization information

The *lifetime* of syncrhonization information should be set based on the expected drift of modem clocks. Lifetime is defined as the time for the expected clock drift (scaled by speed of sound in water) to exceed

the required range estimation accuracy. If a network uses modems with low-drift clocks (such as oven-controlled oscillators), the lifetime can be quite long (hours to days). Without low-drift clocks, reasonable lifetimes may only be in the order of several minutes to tens of minutes.

Why do clocks drift?

Most electronics use crystal oscillators for timekeeping. A crystal oscillator is an electronic circuit that uses the mechanical resonance of a vibrating piezoelectric crystal to create an electrical signal with a desired frequency. The resonant frequency depends on size, shape, elasticity, and the speed of sound in the material. Due to manufacturing tolerences, these properties are not exactly identical across manufactured crystals, and so different crystals designed for the same nominal frequency produce slightly different frequency signals. Furthermore, as the operating temperature of the crystal changes, its material properties change, and so does its resonant frequency. These differences in frequency are tiny, but over long periods of time, the differences accumulate and cause the clocks to drift.

For applications where drift is undesirable, temperature-compensated crystal oscillators (TCXO) or oven-controlled crystal oscillators (OCXO) may be used. TCXOs try to adjust their oscillation frequency electronically, to compensate for temperature changes. OCXOs, on the other hand, try to maintain a constant temperature with a mini-oven around the crystal. For very sensitive applications, atomic clocks may be used for even lower drift. But given long enough time, even the most precise of these oscillators will accumulate tiny errors and the clocks will eventually drift!

The minimum and maximum valid range settings control what the RANGING service considers to be a *bad range* — a range measurement that is unlikely to occur in reality (e.g. negative values, or ranges much further than the communication ability of the modems). Frequent bad ranges to a node are used to detect that the node synchronization information is invalid and should be discarded. The number of `BadRangeNtf` before discarding the synchronization information is specified as `maxBadRangeCnt`.

16.2. Examples

In order to understand how the RANGING service provides OWTT and TWTT ranging, it is instructive to try a few examples using the Netiquette 3-node network simulation (`bin/unet samples/netq-network.groovy`). Start the simulation, and connect to node A:

```
> agentsForService(org.arl.unet.Services.RANGING)  ①
[ranging]
> ranging
<<< Ranging >>>

[org.arl.unet.phy.RangeParam]
  channel = 1                                      ②
  lifetime = 0                                     ③
  maxBadRangeCnt = 10
  maxRange = 6500.0
  minRange = -10.0

> range host('B')                                  ④
370.98
> ranging << new RangeReq(to: host('B'))           ⑤
AGREE
ranging >> RangeNtf:INFORM[from:31 to:232 range:371.0 offset:-256067128]
> ntf.range                                        ⑥
370.98
```

① We see that the `ranging` agent provides the RANGING service on the node.

② The CONTROL channel (channel 1) is being used for ranging.

③ The `lifetime` is set to 0, indicating that the node clocks may have a large drift.

④ The `range` command provides us the range to node B of almost 1 km.

⑤ The `range` command is implemented by sending a `RangeReq` to the `ranging` agent. We directly send that message. As expected, it leads to a `RangeNtf` message that gives us the same range estimate as the `range` command. The `RangeNtf` also provides us time synchronization information between the nodes (as time difference between the nodes, or `offset`, in microseconds).

⑥ While the `RangeNtf` showed a range of 371.0 m, this was just due to rounding off for display. The actual value in the message is 370.98 m, as reported previously by the `range` command.

16.2.1. Two-way travel time ranging

The range measurement above used TWTT ranging. While node B participated in the range measurement by responding to node A's request for a two-way frame exchange, this is all done quietly and we see nothing on node B's shell. To see what is happening on both nodes, subscribe to the `phy` and `ranging` agent's topics on both nodes. Then repeat the `RangeReq` on node A:

Node A:

```
> subscribe phy
> subscribe ranging
> ranging << new RangeReq(to: host('B'))
AGREE
phy >> TxFrameStartNtf:INFORM[type:CONTROL txTime:2546485580 txDuration:950]
phy >> RxFrameStartNtf:INFORM[type:CONTROL rxTime:2548827417]
phy >> RxFrameNtf:INFORM[type:CONTROL from:31 to:232 protocol:1 rxTime:2548827417 txTime:2292518452 (7
bytes)]
ranging >> RangeNtf:INFORM[from:31 to:232 range:371.0 offset:-256067128]
```

We see that node A transmitted a CONTROL frame. It then received a timestamped CONTROL frame back from node B. The timing information in both frames was used to compute the range and time offset

between the nodes. This was sent back to us as a `RangeNtf`. This is the frame exchange that implements TWTT ranging.

If we look at node B's shell at the same time:

Node B:

```
> subscribe phy
> subscribe ranging
phy >> RxFrameStartNtf:INFORM[type:CONTROL rxTime:2290660289]
phy >> RxFrameNtf:INFORM[type:CONTROL from:232 to:31 protocol:1 rxTime:2290660289 (1 byte)]
phy >> TxFrameStartNtf:INFORM[type:CONTROL txTime:2292518452 txDuration:950]
```

We see that node B received a CONTROL frame and responded back with a CONTROL frame.

We can ask node A for the synchronization information it has gathered:

Node A:

```
> ranging << new SyncInfoReq(to: host('B'))
SyncInfoRsp:INFORM[to:31 offset:-256067128 validTill:1568557167512]
```

We see that it has stored the time offset to node B, along with a validity. However, you'll find that the validity has already expired, since the `lifetime` parameter was set to 0. If you ask for synchronization information on node B, you'll find that it does not have any:

Node B:

```
> ranging << new SyncInfoReq(to: host('A'))
REFUSE: Information unavailable
```

Without synchronization information, OWTT ranging cannot be performed.

16.2.2. Synchronization

If we have low-drift clocks on all our nodes, we can set the `lifetime` parameter of the `ranging` agent to a larger value. Let's do that on all nodes. Also unsubscribe from `phy` to avoid too much clutter, but ensure that you're subscribed to `ranging` on all 3 nodes (node A, node B and node C):

Nodes A, B and C:

```
> ranging.lifetime = 3600
3600
> unsubscribe phy
> subscribe ranging
```

Now, initiate TWTT ranging to from node A to node B again:

Node A:

```
> ranging << new RangeReq(to: host('B'))
AGREE
ranging >> RangeNtf:INFORM[from:31 to:232 range:371.0 offset:-256067128]
```

Not much of a difference here, but if you look at the shell for node B, you'll see a notification:

Node B:

```
ranging >> RangeNtf:INFORM[from:232 to:31 range:371.0 offset:256067128]
```

The information in this `RangeNtf` is the same as the `RangeNtf` on node A, except that the `to` and `from` fields are exchanged, and the `offset` has the opposite sign. This makes sense, since the `RangeNtf` on node B is from node B's perspective.

But why did node B receive this `RangeNtf`? If we did a TWTT from node A, node A transmitted a frame, node B responded, and node A computed the two-way travel time. How did node B get that information to generate the `RangeNtf`? Now that the `lifetime` is non-zero, node A transmits the range and time offset to node B to synchronize the nodes. We can verify this by asking node B for the synchronization information it has gleaned:

Node B:

```
> ranging << new SyncInfoReq(to: host('A'))
SyncInfoRsp:INFORM[to:232 offset:256067128 validTill:1568562001976]
```

In fact, if you look at the shell for node C, you'll see that it hears this information as well, but it does not have any synchronization information to either node A or B:

Node C:

```
> ranging << new SyncInfoReq(to: host('A'))
REFUSE: Information unavailable
> ranging << new SyncInfoReq(to: host('B'))
REFUSE: Information unavailable
```

Let's try TWTT ranging from node A to node C:

Node A:

```
> ranging << new RangeReq(to: host('C'))
AGREE
ranging >> RangeNtf:INFORM[from:74 to:232 range:529.9 offset:630715082]
```

Now, if you check node C, you'll see that it has not only gotten the `RangeNtf`, but also has stored the synchronization information:

Node C:

```
ranging >> RangeNtf:INFORM[from:232 to:74 range:529.9 offset:-630715082]
> ranging << new SyncInfoReq(to: host('A'))
SyncInfoRsp:INFORM[to:232 offset:-630715082 validTill:1568562266302]
```

Checking node B, we find that it has also heard the exchange between nodes A and C, and gotten a `RangeNtf` for it. More interestingly, it has synchronization information (time offset) for node C, although we did not ever do a TWTT exchange between nodes B and C! It has inferred the time offset to node C because it knew the time offset to node A, and overheard the time offset between node A and node C!

Node B:

```
ranging >> RangeNtf:INFORM[from:74 to:232 range:529.9]
> ranging << new SyncInfoReq(to: host('C'))
SyncInfoRsp:INFORM[to:74 offset:886782210 validTill:1568562266192]
```

Based on two TWTT exchanges, node A knows time offset to nodes B and C, node B knows time offset to nodes A and C, node C knows time offet to node A. Now that we have the nodes somewhat synchronized, we are in a position to try out OWTT now.

16.2.3. One-way travel time ranging

Let's transmit a ranging beacon from node A:

Node A

```
> ranging << new BeaconReq()
AGREE
```

On node B and C, we see `RangeNtf` from the OWTT ranging:

Node B

```
ranging >> RangeNtf:INFORM[from:232 to:31 range:371.0]
```

Node C

```
ranging >> RangeNtf:INFORM[from:232 to:74 range:529.9]
```

Any timestamped frame transmission from node A will generate `RangeNtf` on nodes B and C. This can be used to piggyback data (e.g. 42) along with the beacon: `phy << new TxFrameReq(timestamped: true, data: [42])`. This will generate a `RxFrameNtf` on nodes B and C, if you subscribe to `phy`, in addition to the `RangeNtf` messages. This works with both CONTROL and DATA frames.

We can also get node A to request node C to transmit a beacon:

Node A

```
> ranging << new RangeReq(to: host('C'), reqBeacon: true)
AGREE
ranging >> RangeNtf:INFORM[from:74 to:232 range:529.9]
```

This yeilds a `RangeNtf` back on node A, giving range from node C to node A. But since node B hears the beacon, and has synchronization information for node C, it also produces a `RangeNtf` with the range from node C to node B:

Node B

```
ranging >> RangeNtf:INFORM[from:74 to:31 range:615.9]
```

Once you have network time synchronization, you can have a lot of fun with OWTT ranging and beacons!

16.2.4. Expired synchronization information

What happens once synchronization information expires? Does the `ranging` agent no longer get the OWTT `RangeNtf` messages?

The `RangeNtf` messages are still produced, but the message attribute `valid` is set to `false`. This attribute can be used by client agents to initiate a TWTT exchange to renew synchronization information, if necessary. So, if you work with OWTT ranging, remember to check the `valid` attribute of `RangeNtf` messages that you receive, to ensure that they are based on unexpired synchronization information and therefore accurate.

Chapter 17. Node information

`org.arl.unet.Services.NODE_INFO`

The NODE_INFO service provides a single place to collate node-related information that is commonly needed by many agents. It is a special service, in the sense that each node must be configured to have **one and only one** agent providing this service.

17.1. Overview

An agent implementing the NODE_INFO service not only exposes a set of parameters, as described in this section, but also provides some special handling for specific parameters.

17.1.1. Parameters

An agent offering the NODE_INFO service supports several parameters:

- `nodeName` — node name
- `address` — node address
- `addressSize` — address size in bits (valid values are 8 or 16)
- `time` — node time (read-only)
- `canForward` — true if the node will forward datagrams to other nodes (routing)
- `origin` — origin as (latitude, longitude)
- `location` — location as (x, y, z) in meters if origin set, otherwise (latitude, longitude, z)
- `mobility` — true if the node is mobile, false if it is fixed
- `speed` — speed in m/s, if mobile node
- `heading` — heading in degrees, 0 is North, measured clockwise, if mobile node
- `turnRate` — turn rate in degrees/s, measured clockwise, if mobile node
- `diveRate` — dive rate in m/s, if mobile node

Any changes to parameters `nodeName`, `address`, `addressSize`, `origin` or `location` are published as `ParamChangeNtf` to the agent's topic (in addition to the `PARAMCHANGE` topic that all parameter changes are automatically published to — see Chapter 24). This is to facilitate monitoring of changes to these important parameters by other agents, simply by subscribing to the NODE_INFO service provider's topic.

Additionally, if time stability or location accuracy information is available, the following parameters are populated:

- `timeStability` — time stability in ppm
- `locationAccuracy` — location accuracy as (x, y, z) in meters

17.1.2. Notes

- See Section 4.1 for a discussion on `nodeName`, `address` and `addressSize`.

- See Section 5.6 for a discussion on `origin`, `location` and coordinate systems.
- If node `mobility` is enabled, the agent may automatically update `location` based on motion parameters such as `speed`, `heading`, etc.

17.2. Example

If you start the mission2013 network simulation (`bin/unet samples/mission2013-network.groovy`), connect to node 21's shell and type `node`, you'll see the NODE_INFO parameters for the node in this network:

```
> node
<<< NodeInfo >>>

[org.arl.unet.nodeinfo.NodeInfoParam]
  address = 21
  addressSize = 8
  canForward = true
  diveRate = 0
  heading = 0
  location = [-512.0, 248.8, -6.0]
  mobility = false
  nodeName = 21
  origin = [1.217, 103.743]
  speed = 0
  time = Sun Sep 15 20:31:49 SGT 2019
  turnRate = 0
```

Chapter 18. Address resolution

`org.arl.unet.Services.ADDRESS_RESOLUTION`

18.1. Overview

An ADDRESS_RESOLUTION service provider is responsible for address allocation and resolution. The size of the address space is detemined by the `addressSize` parameter of the NODE_INFO service (Chapter 17).

18.1.1. Messages

Agents supporting this service honor the following requests:

- `AddressAllocReq` ⇒ `AddressAllocRsp` / `FAILURE` — request for allocation of address to node
- `AddressResolutionReq` ⇒ `AddressResolutionRsp` / `FAILURE` — resolve node name to address

18.2. Usage and notes

Shell usage of this service via the `host` command is described in Section 4.1. In this section, we show examples of how address allocation and address resolution can be implemented directly by sending messages.

Address allocation is typically required at startup, and usually initiated by the agent providing the NODE_INFO service to populate the `address` parameter of that service. To ask the ADDRESS_RESOLUTION service provider to allocate an address, an agent sends it a `AddressAllocReq`. The allocation may depend on the node name, and so the request must contain the node name.

We can start the 2-node network, and manually test this on the shell of node A:

```
> a = agentForService(org.arl.unet.Services.ADDRESS_RESOLUTION);
> a << new AddressAllocReq(name: 'A')
AddressAllocRsp:INFORM[address:232]
```

Address resolution is performed via the `AddressResolutionReq` message. The `host` command sends this message on your behalf, and shows you the response:

```
> a << new AddressResolutionReq(name: 'A')
AddressResolutionRsp:INFORM[address:232 name:A]
> ans.address
232
> host('A')
232
```

While the address allocation and resolution processes may seem very similar, there is a conceptual difference between the two. Address allocation is performed for a new node without an address. The address allocation process associates it with an address. Address resolution is performed to find the address that was assigned to a node.

The default ADDRESS_RESOLUTION service provider uses a hashing function to map node names to addresses. This enables it to allocate and resolve addresses without generating network traffic, as the hashing function generates the same address for a given name on each node. Because the hashing maps a large name space to a small address space, there is always the chance that two names map to the same address; we require that the network architect check this manually, and assign node names such that there are no address conflicts.

Network designers and protocol developers should not rely on the ADDRESS_RESOLUTION service provider being based on a hashing function for correct operation of the network.

Chapter 19. Medium access control

`org.arl.unet.Services.MAC`

19.1. Overview

Agents offering the medium access control (MAC) service advise other agents on when they may be permitted to make transmissions, in an effort to reduce collisions and improve network throughput.

MAC protocols that use PDUs for channel reservation may support piggybacking of client data in the PDU. If such support is available, it is advertised using a non-zero `reservationPayloadSize` parameter. A `ReservationReq` should provide the payload data to be sent to a peer node (as part of RTS or equivalent PDU) to whom the reservation is made. If that node wishes to send payload data back (as part of CTS or equivalent PDU), it may send a `ReservationAcceptReq` in response to a `ReservationStatusNtf` to provide its payload data.

Protocol data units (PDUs) are protocol-specific datagrams exchanged by nodes in a network. MAC protocls that use a handshake often use three basic type of PDUs — request to send (RTS), clear to send (CTS) and acknowledgement (ACK).

What is a payload?

We talk about MAC service's support for payloads quite a bit in this chapter, but what exactly is a payload?

A *payload* is a few bytes of data that can be carried by a MAC PDU on behalf of the user or another agent, without consuming significant additional resources (time or energy). It is essentially an optimization for a low bandwidth network, reducing the need for additional datagrams to be transmitted to convey a few bytes of side information from other agents. For example, a LINK agent might send power control information as payload during a CTS-RTS exchange to optimize transmission power. Or it might send channel state information to aid in adaptive modulation to optimize link throughput.

19.1.1. Messages

Agents supporting the MAC service provide messages to request, grant and cancel reservations:

- `ReservationReq` ⇒ `ReservationRsp` / `REFUSE` — request a reservation
- `ReservationCancelReq` ⇒ `AGREE` / `REFUSE` — cancel a reservation
- `ReservationAcceptReq` ⇒ `AGREE` / `REFUSE` — request piggybacking of payload in a reservation PDU, typically sent by a client on receiving a `ReservationStatusNtf[status: REQUEST]` notification
- `TxAckReq` ⇒ `AGREE` / `REFUSE` — request transmission of acknowledgement payload
- `ReservationStatusNtf` — sent to requestor or agent's topic when a reservation-related events occur

19.1.2. Parameters

Agents offering the MAC service support the following parameters:

- `channelBusy` — true if channel is busy, false otherwise
- `reservationPayloadSize` — maximum size of payload (bytes) that can be piggybacked in a reservation PDU
- `ackPayloadSize` — maximum size of acknowledgement (bytes) that can be included in an ACK PDU
- `maxReservationDuration` — maximum duration of reservation in seconds
- `recommendedReservationDuration` — recommended duration of reservation in seconds (null, if unspecified)

19.1.3. Capabilities

Agents may support several optional capabilities:

RELIABILITY

An agent advertising this capability must be able to send acknowlegements as part of the MAC protocol. The agent must support the `TxAckReq` request to provide acknowledgement payload to be transmitted to the peer node at the end of the reservation. On reception, this should generate a `RxAckNtf` on the peer node.

PRIORITY

Agents advertising this capability must honor priority settings in the reservation request.

TTL

Agents advertising this capability must honor time-to-live settings in the reservation request.

TIMED_RESERVATION

Agents advertising this capability must support scheduling of reservations in the future, through the use of the `startTime` attribute of the `ReservationReq`.

19.2. Basic MAC functionality

MAC agents advise other agents that wish to transmit (we shall call them *clients*) on when they may do so. MAC agents make channel reservations on behalf of their clients, as necessary. Some MAC protocols such as Aloha and TDMA may not require explicit handshake for reservation, while others such as MACA and FAMA may involve control packet exchanges between peer MAC agents on various nodes. In either case, a typical client with data to transmit starts by asking the prevailing MAC agent for a channel reservation:

```
// client wishes to transmit data to "destination" for specified "duration"
def mac = agentForService(Services.MAC)
if (mac) {
  def req = new ReservationReq(recipient: mac, to: destination, duration: duration) ①
  def rsp = request(req)
  if (rsp && rsp.performative == Performative.AGREE) {
    def ntf = receive(ReservationStatusNtf, timeout)       ②
    if (ntf && ntf.inReplyTo == req.messageID && ntf.status == ReservationStatus.START) {
      //    :
      // transmit data for requested duration
      //    :
    }
  }
}
```

① Send a channel reservation request.

② Wait for a channel reservation notification.

In the above sample code, error handling has been omitted for simplicity. In reality, you would want to have else clauses to handle reservation failures. The MAC agent not only sends a `ReservationStatusNtf[status: START]` notification, but also a `ReservationStatusNtf[status: END]` notification at the end of the reservation duration. The sample code above ignores this notification, but a well-behaved client should ensure that the transmission does not exceed the requested duration.

19.3. Working with MAC payloads

Messages such as `ReservationReq` and `ReservationStatusNtf` may carry payloads, when the MAC protocol supports them. When payloads are supported, additional messages such as `ReservationAcceptReq`, `TxAckReq` and `TxAckNtf` are available for clients to provide payloads to the MAC service provider to piggyback on the MAC PDUs. A typical exchange is illustrated in Figure 8.

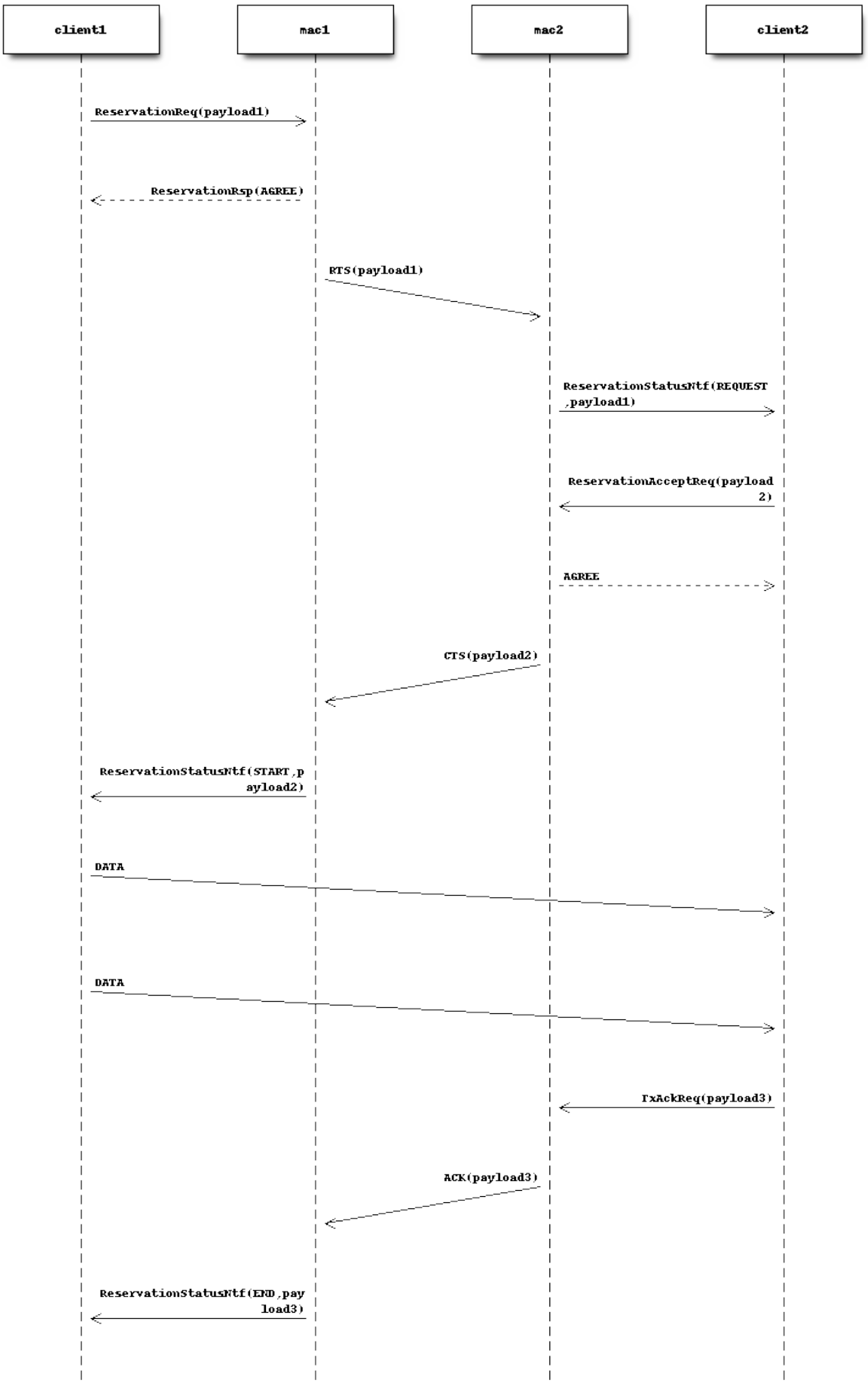


Figure 8. Typical message exchange for MAC with payloads and ACK.

For a MAC reservation initiated by node A with node B, we elaborate on the steps for a full reservation lifecycle with payloads:

1. On node A, the client (agent) sends a `ReservationReq` to the MAC (agent), with an optional payload. The MAC accepts the request.
2. MAC on node A sends a RTS PDU with the payload to the MAC on node B.
3. MAC on node B generates a `ReservationStatusNtf[status: REQUEST]` message and publishes it on its topic. A client subscribing to this topic receives the notification.
4. If the client on node B wants to send back some payload with the CTS PDU, it immediately sends a `ReservationAcceptReq` to the MAC, with the payload.
5. The MAC accepts the request and responds to node A's MAC with a clients PDU containing the payload.
6. The payload is delivered to the client on node A as part of a `ReservationStatusNtf[status: START]` message marking the start of the reservation time.
7. During the reservation, the two nodes exchange data as they wish.
8. If the client on node B wishes to provide an acknowledgment (with a payload), it sends a `TxAckReq` message before the reservation duration ends, and the MAC on node B accepts.
9. The MAC on node B sends an ACK PDU with the payload to the MAC on node A. The ACK PDU marks the end of the channel reservation. The MAC delivers this acknowledgment payload to the client on node A as a part of the `ReservationStatusNtf[status: END]` message.
10. If node B does not send an ACK PDU, when the channel reservation ends, the MAC on node A sends a `ReservationStatusNtf[status: END]` message to its client.

19.4. Examples

Sample MAC implementations are illustrated in Chapter 28.

Chapter 20. Single-hop links

`org.arl.unet.Services.LINK`

20.1. Overview

Agents offering the LINK service provide single-hop communication.

Single-hop here refers to a single hop in the Unet sense. For example, a link may be provided over wireless RF network that has multiple physical hops (e.g. using UDP/IP). However, as long as the link does not pass through multiple Unet nodes, it is considered a logically single-hop link.

All agents supporting the LINK service must also support the DATAGRAM service (Chapter 13).

It is recommended that agents offering the LINK service provide reliability, when requested. Agents that are able to provide reliability, do so by advertising the DATAGRAM service capability RELIABILITY.

LINK service providers using the PHYSICAL service should also consult the MAC service to determine when they should transmit.

In a typical Unet, gateway nodes may have several LINK service providers, with the ROUTING service (Section 21.2) provider forwarding datagrams across links.

20.1.1. Parameters

Agents offering the LINK service may support the following parameter:

- `dataRate` — nominal data rate of link in bps (0 if unknown)

20.2. ReliableLink

Start the 2-node network and connect to node A:

```
> agentsForService org.arl.unet.Services.LINK
[uwlink]

> uwlink
<<< ReliableLink >>>

[org.arl.unet.DatagramParam]
  MTU = 848

[org.arl.unet.link.LinkParam]
  dataRate = 731.4286

[org.arl.unet.link.ReliableLinkParam]
  acks = 2
  controlChannel = 1
  dataChannel = 2
  mac = mac
  maxPropagationDelay = 2.5
  maxRetries = 2
  phy = phy
  reservationGuardTime = 0.5
```

We see that in the 2-node network simulation, the only agent that provides the link service is the `uwlink` agent of type `ReliableLink`. This agent fragments large datagrams, and transmits a batch of frames at a time, before waiting for an acknowledgement from the peer node. Unacknowledged frames are retransmitted until all frames are delivered, or there are too many retries. Once all frames are received, the peer node's `uwlink` agent reassembles the datagram and delivers it.

`ReliableLink` provides the LINK service for all underwater links in Unet basic stack that ships as part of the community edition.

With the default PHYSICAL service settings, the nominal data rate provided by this link is 731 bps, and that only 848 or less bytes may be transferred per datagram. The actual data rate may differ, depending on the size of the datagram, reliability settings, and the channel conditions.

We also see that `ReliableLink` provides a set of configurable parameters:

`acks`
: Number of acknowledgements to use for reliable data transfer. Since a lost acknowledgement frame results in retransmission of the entire batch of frames, multiple acknowledgements are used to improve the robustness of the acknowledgement frame.

`controlChannel`
: Frame type to use for control information. This is usually the CONTROL frame type.

`dataChannel`
: Frame type to use for data frames. This is usually the DATA frame type.

`mac`
: MAC service provider to use for reserving the channel. This is automatically discovered during startup. Setting this to `null` disables MAC reservation.

`maxPropagationDelay`

Maximum expected propagation delay for the link (in seconds). This should be set based on the expected single-hop communication range, and the sound speed (in case of acoustic links). This parameter is used to determine expected round-trip time for setting timeouts for acknowledgement frames.

`maxRetries`

Maximum number of retries per frame. Once the maximum number of retries is exceeded, a datagram transfer is deemed to have failed.

`phy`

PHYSICAL service provider for data transmission. This is automatically discovered during startup, but may be configured manually on gateway nodes with multiple PHYSICAL service providers.

`reservationGuardTime`

Guard time (in seconds) that is included in a MAC reservation of the channel. The guard time allows for small timing variability in transmission and small delays in response from peer node.

20.3. ECLink

In the Unet premium stack, `ECLink` replaces `ReliableLink` as the default LINK service provider for underwater links.

`ECLink` uses an erasure correction code (type of error correction code that deals with lost frames) to reduce the protocol overhead required for retransmissions in a lossy channel. This usuaully results in significantly better performance than `ReliableLink` in poor channel conditions, and when transferring large datagrams.

If you have a modem with the commercial version of UnetStack3, it'll have `ECLink` loaded as the default LINK service provider:

```
> uwlink
<<< ECLink >>>

[org.arl.unet.DatagramParam]
  MTU = 3145632

[org.arl.unet.link.ECLinkParam]
  controlChannel = 1
  dataChannel = 2
  mac = mac
  maxBatchSize = 65534
  maxPropagationDelay = 3.0
  maxRetries = 2
  minBatchSize = 3
  phy = phy
  reliability = false
  reliableExtra = 0.2
  unreliableExtra = 0.3

[org.arl.unet.link.LinkParam]
  dataRate = 731.4286
```

We see that the `MTU` for `ECLink` is quite large (as compared to `ReliableLink`), as `ECLink` can efficiently

transfer large amounts of data. While the `dataRate` parameter advertises a similar nominal rate as with `ReliableLink`, you'll find that `ECLink` yields better practical performance when transferring large files, and in poor channel conditions.

The `phy`, `controlChannel`, `dataChannel`, `mac`, `maxRetries`, and `maxPropagationDelay` parameters of `ECLink` are similar to the ones in `ReliableLink`. However, `ECLink` has several additional parameters that control performance:

`minBatchSize`
: Minimum number of frames to send in each batch.

`maxBatchSize`
: Maximum number of frames to send in each batch.

`reliability`
: Default reliability for a datagram transfer, if a `DatagramReq` does not specify reliability (`null`).

`reliableExtra`
: Fraction of extra frames to transmit for erasure correction, during reliable datagram transfer (using acknowledgements to determine retries). A value of 0.2 indicates 20% extra frames are transmitted. This allows for 20% frame loss without the need for retries.

`unreliableExtra`
: Fraction of extra frames to transmit for erasure correction, during unreliable datagram transfer (no acknowledgement or retries). A value of 0.3 indicates 30% extra frames are transmitted. This allows for successful datagram transfer with as much as 30% frame loss.

Chapter 21. Routing and route maintenance

21.1. Overview

The ROUTING and ROUTE_MAINTENANCE services work closely to provide multi-hop communications. The ROUTING serice provider is responsible for maintaining a routing table, and for routing datagrams according to the table. The ROUTE_MAINTENANCE service provider, on the other hand, is responsible for discovering new routes and providing updated routing information to the ROUTING service provider.

If a network only requires static routes, the ROUTING service provider is sufficient to provide the functionality. In case of networks with dynamic route discovery, a ROUTE_MAINTENANCE service provider discovers routes (or route changes) and publishes `RouteDiscoveryNtf` messages. The ROUTING service provider subscribes to these messages and updates its routing tables.

Both services are described below.

21.2. Routing service

`org.arl.unet.Services.ROUTING`

Agents offering the ROUTING service provide multi-hop communication.

All agents supporting the ROUTING service must also support the DATAGRAM service (Chapter 13).

It is recommended that agents offering the ROUTING service provide reliability, when requested. Agents that are able to provide reliability, do so by advertising the DATAGRAM service capability RELIABILITY.

The ROUTING service currently does not define a way to add, update or delete static routes in the routing table. Dynamic routes may be added/updated using the `RouteDiscoveryNtf` messages. An agent implementing this service may choose to provide agent-specific messages or parameters to manage the routes. The agent should provide `routes`, `addroute`, `delroute` and `delroutesto` commands (see Section 6.3) for user interaction from the shell.

21.3. Route maintenance service

`org.arl.unet.Services.ROUTE_MAINTENANCE`

Agents offering the ROUTE_MAINTENANCE service generate `RouteDiscoveryNtf` messages to allow ROUTING service providers to maintain routing tables.

21.3.1. Messages

Agents providing the ROUTE_MAINTENANCE service support the following messages:

- `RouteDiscoveryReq` ⇒ `AGREE` / `REFUSE` / `FAILURE` — start route discovery to a specified node
- `RouteTraceReq` ⇒ `AGREE` / `REFUSE` / `FAILURE` — trace current route to a specified node

- `RouteDiscoveryNtf` — sent to the agent's topic when a route is discovered
- `RouteTraceNtf` — sent to requestor when a requested trace is successfully completed

21.4. Router and the route discovery protocol

The `Router` class (agent name `router`) provides the ROUTING service in the standard stack. Apart from supporting the `routes`, `addroute`, `delroute` and `delroutesto` commands, this agent exposes two parameters:

- `auto1hop` — automatically assume single-hop routes available, if no entry for destination node in routing table
- `defaultLink` — default LINK service provider to use for datagram transmission, if unspecified while adding a route

Without `auto1hop` enabled, every route must be explicitly added to the routing table (even when the node is accessible over a single hop). By enabling `auto1hop`, we tell the router than any node that isn't explicitly added to the routing table is assumed to be accessible over a single hop. This is the default setting:

```
> router
<<< Router >>>

[org.arl.unet.DatagramParam]
  MTU = 3145630

[org.arl.unet.net.RouterParam]
  auto1hop = true
  defaultLink = uwlink
```

The `RouteDiscoveryProtocol` class (agent name `rdp`) provides the ROUTE_MAINTENANCE service in the standard stack. This agent has no configurable parameters.

In Chapter 6, we explored several examples of how to set up networks with static and dynamic routes. To find out more about routing, type `help router` in the shell:

```
> help router
router - access to routing service

Examples:
  routes              // display routing table
  routes 2            // display routes to node 2
  addroute 27, 29     // add a route to node 27 via node 29
  delroute 2          // delete route number 2
  delroutesto 27      // delete all routes to node 27
  delroutes           // delete all routes
  trace 27            // trace route to node 27
  ping 27             // check if node 27 is accessible

Parameters:

- router.MTU - maximum data transfer size
- router.auto1hop - automatically assume single hop routes
- router.defaultLink - default link to use

Commands:

- routes - print routing table
- addroute - add a route to the routing table
- delroute - delete a route from the routing table
- delroutesto - delete all routes to specified node from the routing table
- delroutes - delete all routes from the routing table
```

You can also type `help` followed by any of the commands above to get more information on the usage of that command.

Chapter 22. Transport service

`org.arl.unet.Services.TRANSPORT`

22.1. Overview

Agents offering the TRANSPORT service provide end-to-end reliability and fragmentation/reassembly for large datagrams. They may also support connection-oriented services for data streaming. Agents providing this service typically use the ROUTING service for multi-hop delivery of data.

All agents supporting the TRANSPORT service must also support the DATAGRAM service (Chapter 13), along with the RELIABILITY and FRAGMENTATION capabilities. It is also recommended that they support the CANCELLATION and PROGRESS capabilities, since datagrams at this level are likely to be large.

There are no special messages or parameters defined by the TRANSPORT service, but agents providing this service may expose additional parameters to configure the transport protocol in use.

22.2. Stop-and-wait transport

The default implementation of the TRANSPORT service is the `SWTransport` class. If you start the 2-node network simulation and connect to node A, you can explore the configurable parameters that it advertises:

```
> transport
<<< SWTransport >>>

[org.arl.unet.DatagramParam]
  MTU = 16777215

[org.arl.unet.transport.SWTransportParam]
  dsp = router
  maxHops = 3
  maxRetries = 2
  reportProgress = false
  timeoutPerHop = 90.0
```

We briefly explain each parameter below:

`dsp`
: Datagram service provider. This is the agent that is used to deliver datagrams. Using `router` for this parameter enables multi-hop networks.

`maxHops`
: Maximum number of hops expected to destination nodes.

`maxRetries`
: Maximum number of end-to-end retries, if end-to-end acknowledgements are not received. We recommend that link level reliability be enabled to reduce end-to-end retries. This is easily done by setting the `reliability` parameter for a route, or by enabling `reliability` at the LINK service provider (if it offers such a parameter).

`reportProgress`

Setting this parameter to `true` asks the `transport` agent to send out periodic `DatagramProgressNtf` messages to the requester (on the transmitting node) or on the agent's topic (on the receiving node), when transferring large datagrams.

`timeoutPerHop`

Timeout (in seconds) per hop, for datagram transfer.

Next, let's try a 2048-byte datagram transfer from node A to node B with progress reports:

```
> transport << new DatagramReq(to: 31, data: new float[2048], reliability: true)
AGREE
transport >> DatagramProgressNtf:INFORM[id:2 to:31 to:(838/2048 bytes, 40%)]
transport >> DatagramProgressNtf:INFORM[id:2 to:31 to:(1676/2048 bytes, 81%)]
transport >> DatagramProgressNtf:INFORM[id:2 to:31 to:(2048/2048 bytes, 100%)]
transport >> DatagramDeliveryNtf:INFORM[id:d76a56bf-58f6-4a9c-8a19-7a0a6ce8bcd4 to:31]
```

The entire transfer will take a few minutes. During that time, we get periodic `DatagramProgressNtf` reports showing how much of the data transfer was completed.

Chapter 23. Remote access

`org.arl.unet.Services.REMOTE`

23.1. Overview

Agents offering the REMOTE service provide text messaging, file transfer, and remote command execution services across a network.

While the REMOTE service provides a field for credentials to be included in a request, it does not specify how authentication and security should be handled by an agent. It is important for developers and users of the REMOTE service to give due consideration to network security before enabling this service on their network.

23.1.1. Messages

Agents providing the REMOTE service support the following messages:

- `RemoteTextReq` ⇒ `AGREE` / `REFUSE` / `FAILURE` — send a text message to remote node
- `RemoteFileGetReq` ⇒ `AGREE` / `REFUSE` / `FAILURE` — download a file from remote node
- `RemoteFilePutReq` ⇒ `AGREE` / `REFUSE` / `FAILURE` — upload a file to remote node
- `RemoteExecReq` ⇒ `AGREE` / `REFUSE` / `FAILURE` — execute a shell command on the remote node
- `RemoteTextNtf` — sent to the agent's topic when a text message from another node arrives
- `RemoteFileNtf` — sent to the agent's topic when an incoming file transfer from another node is completed
- `RemoteSuccessNtf` — sent to a requester when a remote operation is successfully completed, if an acknowledgement was requested
- `RemoteFailureNtf` — sent to a requester when a remote operation fails, if an acknowledgement was requested

23.2. RemoteControl

Start the 2-node network and connect to node A:

```
> agentsForService org.arl.unet.Services.REMOTE
[remote]
> remote
<<< RemoteControl >>>

[org.arl.unet.remote.RemoteControlParam]
  cwd = /Users/mandar/Projects/unet/scripts
  dsp = transport
  enable = false
  groovy = true
  reliability = true
  shell = websh
```

We see that the REMOTE service is provided by the `remote` agent of type `RemoteControl`. The agent's behavior is controlled by several parameters:

`cwd`
: Current working directory. This directory is the reference location for all file transfers and command execution.

`dsp`
: Datagram service provider. This is the agent that is used to deliver datagrams.

`shell`
: SHELL service provider (see Chapter 26) used to execute commands. When a remote command is to be executed, a request is sent to this shell agent to execute the command.

`groovy`
: Enable Groovy extensions for shell commands. This should only be enabled if the `shell` is a Groovy shell. The only Groovy extension defined at this point in time is the `?` shortcut. Starting a command with a `?` automatically sends the output of the command back to the requesting node (e.g. `?phy.MTU` is equivalent to `tell me, phy.MTU as String`). We have encountered the use of this extension before in Section 5.5.

`reliability`
: Setting this to `true` enables `reliability` for all datagrams used by the agent.

`enable`
: Setting this to `true` enables incoming remote file operations and remote commands. The parameter is `false` by default, for security reasons. Outgoing remote operations are always enabled, irrespective of this parameter. Incoming and outgoing text messaging is also always enabled when this agent is loaded.

The default `RemoteControl` agent in the basic stack does not implement any authentication. Once enabled, it will accept all file transfer and remote command execution requests. Care should be taken not to `enable` it in networks where malicious hackers may be able to send harmful requests to your node.

The `phy[CONTROL].scrambler` and `phy[DATA].scrambler` parameters available in many UnetStack-based modems provide a basic level of protection against malicious hackers by scrambling each transmission in the modem. Setting the `scrambler` to a "secret" value (64-bit key) in all your nodes enables this basic protection. Do bear in mind that scrambling is not a crypotgraphically strong technique, and will not protect you from a serious hacker. The technique is also vulnerable to playback attack, even if the malicious hacker is unable to unscramble your frame.

All remote commands (`tell`, `fget`, `fput`, `rsh`, and `ack`) encountered in Section 5.4 and Section 5.5 are implemented by the shell using the above messages. For example, the same effect as the `tell` command can be achieved by directly sending the `RemoteTextReq` message to the `remote` agent on node A:

```
> remote << new RemoteTextReq(to: host('B'), text: 'hello!', ack: true)
AGREE
remote >> RemoteSuccessNtf:INFORM[RemoteTextReq:REQUEST[to:31 text:hello! ack:true]]
```

We should see the text message delivered on node B:

```
[232]: hello!
```

We encourage you to re-read Section 5.5 and explore the help (`help remote`) to fully appreciate the use of this service.

Chapter 24. State persistence

`org.arl.unet.Services.STATE_MANAGER`

24.1. Overview

An agent offering the STATE_MANAGER service provides a way to save the state (parameter values) of specified (or all) agents.

Such an agent typically subscribes to the `PARAMCHANGE` topic and monitor `ParamChangeNtf` for all parameter changes for all agents. It then helps persist selected agents' parameter values between reboots.

24.1.1. Messages

STATE_MANAGER service providers honor the following messages:

- `SaveStateReq` ⇒ `AGREE` / `REFUSE` / `FAILURE` — save agent state to a file
- `ClearStateReq` ⇒ `AGREE` / `REFUSE` / `FAILURE` — clear agent state in memory, and track only parameter changes henceforth

The `SaveStateReq` message causes the agent state (changed parameters) to be persisted to a Groovy script file in the `scripts` folder. The default name of the file is `saved-state.groovy`, and this file is automatically loaded on startup. However, the `SaveStateReq` message can specify an alternate filename to persist the state in. In such cases, the file is run manually when the state is to be restored.

24.2. Examples

Fire up unet audio (`bin/unet audio`) to test out how state persistence works:

```
> plvl
phy[1].powerLevel = -10.0
phy[2].powerLevel = -10.0
phy[3].powerLevel = -10.0
phy[4].powerLevel = -10.0
phy.signalPowerLevel = -10.0
> plvl -40
OK
> shutdown
```

Now start unet audio again, and you'll find that the `plvl` state was not retained through reboots:

```
> plvl
phy[1].powerLevel = -10.0
phy[2].powerLevel = -10.0
phy[3].powerLevel = -10.0
phy[4].powerLevel = -10.0
phy.signalPowerLevel = -10.0
```

We can ask it to retain the state:

```
> plvl -40
OK
> savestate                       ①
AGREE
> ls
README.md [759 bytes]
saved-state.groovy [156 bytes]    ②
> shutdown
```

① The `savestate` command just sends a `SaveStateReq` message to the STATE_MANAGER service provider.

② The `saved-state.groovy` file is created with all the parameter changes to all agents.

Start unet audio again, and you'll find that the state is retained:

```
> plvl
phy[1].powerLevel = -40.0
phy[2].powerLevel = -40.0
phy[3].powerLevel = -40.0
phy[4].powerLevel = -40.0
phy.signalPowerLevel = -40.0
> shutdown
```

The `saved-state.groovy` is human-readable, and you'll see that it simply contains the Groovy code to set the parameters required to restore the state:

saved-state.groovy:

```
def phy = agent('phy')
phy[1].powerLevel = -40.0
phy[2].powerLevel = -40.0
phy[3].powerLevel = -40.0
phy[4].powerLevel = -40.0
phy.signalPowerLevel = -40.0
```

Delete this file and start unet audio again:

```
> help savestate
savestate - save state of all or specified agent in Groovy script format

Examples:
  savestate 'pandan'          // save current state of all agents
  savestate 'pandan', 'phy'   // save current state of specified agent
  savestate 'pandan', phy     // save current state of specified agent
  savestate                   // save current state in "saved-state.groovy"

> help clrstate
clrstate - set current state as the baseline for savestate

Example:
  clrstate                    // set baseline state
  phy[1].powerLevel = -10     // change parameters
  savestate                   // save changed parameters
```

The help shows you that the `savestate` command can be used to save the state of individual agents, if you wish, to a filename of your choice. If you save the state to a different filename, it is not automatically

restored on startup. But you can restore it easily with a single command (name of the file):

```
> plvl
phy[1].powerLevel = -10.0
phy[2].powerLevel = -10.0
phy[3].powerLevel = -10.0
phy[4].powerLevel = -10.0
phy.signalPowerLevel = -10.0
> plvl -40
OK
> savestate 'p40', phy            ①
AGREE
> plvl -10                        ②
OK
> ls
README.md [759 bytes]
p40.groovy [156 bytes]            ③
> p40                             ④
> plvl
phy[1].powerLevel = -40.0
phy[2].powerLevel = -40.0
phy[3].powerLevel = -40.0
phy[4].powerLevel = -40.0
phy.signalPowerLevel = -40.0
```

① Save the `plvl -40` state to a file called `p40.groovy`.

② Change the state.

③ The state is saved in the `p40.groovy` file in the `scripts` folder.

④ Command `p40` runs the `p40.groovy` file to restore the state to `plvl -40`.

Startup scripts

While the STATE_MANAGER service provides a convenient way to save the current state, sometimes you may wish to write a customized startup script that sets up the node the way you wish. This can be achieved via the `setup.groovy`, `startup.groovy` and `fshrc.groovy` scripts in the `scripts` folder.

If you create a `setup.groovy` script, the default stack is disabled, allowing you to customize the agents that are loaded. The only agents that are automatically loaded if this script is present are the NODE_INFO, PHYSICAL and SHELL agents. The `setup.groovy` script is called during the setup phase of bootup, when agents are being loaded. It is the responsibility of the `setup.groovy` script to setup the rest of the stack by loading appropriate agents.

If you create a `startup.groovy` script, it is called after all agents are loaded and the stack is fully initialized. You may put Groovy commands in this script to customize your agent parameters and other settings. The `startup.groovy` script is called before the `saved-state.groovy` script, if one exists.

If you create a `fshrc.groovy` script, it is executed by each Groovy shell agent, when it is loaded. This allows customization of commands and variables available in the shell for user interaction.

Chapter 25. Scheduler

`org.arl.unet.Services.SCHEDULER`

25.1. Overview

Agents offering the SCHEDULER service provide a way to schedule sleep/wake tasks in the future.

25.1.1. Messages

The following messages are used by the SCHEDULER service:

- `AddScheduledSleepReq` ⇒ `AGREE` / `REFUSE` / `FAILURE` — add a new scheduled sleep
- `RemoveScheduledSleepReq` ⇒ `AGREE` / `REFUSE` / `FAILURE` — remove a scheduled sleep
- `GetSleepScheduleReq` ⇒ `AGREE` / `REFUSE` / `FAILURE` — get all the scheduled sleep/wake times
- `WakeFromSleepNtf` — sent to agent's topic just after node wakes up from a sleep

25.1.2. Parameters

Only parameter is required by the SCHEDULER service:

- `etc` — current date/time

25.2. Sleep/wake scheduling

The unet simulator currently does not support sleep/wake scheduling. While unet audio supports the SCHEDULER service, it does not actually put your computer to sleep. Therefore you can experiment with creating and managing schedules on unet audio, without worrying about your computer going to sleep. Start up unet audio (`bin/unet audio`) and connect to its shell:

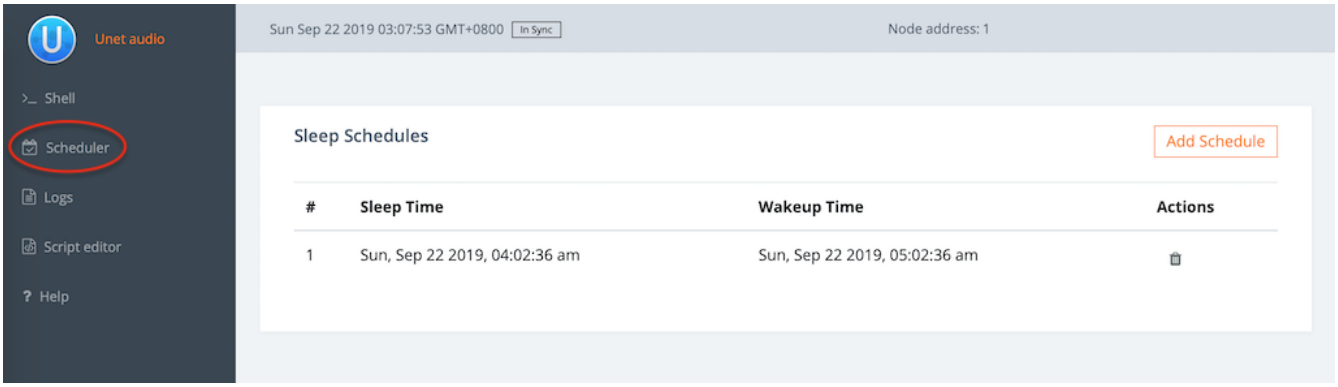
```
> agentsForService org.arl.unet.Services.SCHEDULER
[phy]

> phy.rtc
Sun Sep 22 02:58:20 SGT 2019

> help scheduler
scheduler - access to scheduling service

Commands:

- addsleep - schedule sleep and wakeup of the modem
- showsleep - shows sleep/wakeup schedule
- rmsleep - removes sleep/wakeup schedule

> help addsleep
addsleep - schedule sleep and wakeup of the modem

Examples:
  addsleep 1507014548, 1507014558  // sleep from epoch 1507014548 to 1507014558
  addsleep 1507014558              // sleep immediately until 1507014548
  addsleep 10.s.later, 20.s.later  // sleep 10s later and wake up 20s later
  addsleep 20.s.later              // sleep immediately and wake up 20s later
  addsleep 20.s.later, forever     // sleep 20s later forever
  addsleep                         // sleep immediately forever

> addsleep 1.hour.later, forever
AGREE
> showsleep
bbfb3b79-942c-4fba-bc37-ab9d18dabda5: Sun Sep 22 04:00:00 SGT 2019 to eternity
> rmsleep 'bbfb3b79-942c-4fba-bc37-ab9d18dabda5'
AGREE
> showsleep

> addsleep 1.hour.later, 2.hours.later
AGREE
> showsleep
87de2dec-db29-4b34-a93c-775bfe8c68c5: Sun Sep 22 04:02:36 SGT 2019 to Sun Sep 22 05:02:36 SGT 2019
```

We see that the `phy` agent provides the SCHEDULER service in unet audio. We add a sleep schedule, check that it shows up, remove it, and check that it is deleted. We then add another schedule.

The `addsleep`, `showsleep`, and `rmsleep` commands use the `AddScheduledSleepReq`, `GetSleepScheduleReq`, and `RemoveScheduledSleepReq` messages to achieve their functionality. We can manually send this messages to confirm this, if we like:

```
> phy << new GetSleepScheduleReq()
SleepScheduleRsp:INFORM[(1 item)]
> ans.sleepSchedule
[87de2dec-db29-4b34-a93c-775bfe8c68c5: Sun Sep 22 04:02:36 SGT 2019 to Sun Sep 22 05:02:36 SGT 2019]
```

We can also use the web interface to manage the sleep schedule, if we like:



A big advantage of working with the web interface for sleep scheduling is that the user interface displays date/time in a human readable format. On the other hand, programmatic access with messages requires times to be specified as Unix epoch time.

25.3. Epoch time

The Unix epoch is the number of seconds that have elapsed since January 1, 1970 (midnight UTC), not counting leap seconds. While computers find it easy to work with epoch time, we find it hard to interpret. So UnetStack introduces syntactic sugar such as "1.hour.later" that computer the Unix epoch time 1 hour from now:

```
> 1.hour.later
1569097078

> 2.minutes.later
1569093616
```

There are online calculators that'll help you convert between Unix epoch time and human readable date/time. This works well, if you need to manually convert a few date/times, but what if you needed to do this programmatically? Java provides simple APIs to deal with date/times:

```
> import java.time.Instant
> Instant.now().epochSecond                          ①
1569094526
> Instant.ofEpochSecond(1569093616)                  ②
2019-09-21T19:20:16Z
> Instant.parse("2019-09-21T19:20:16Z").epochSecond  ③
1569093616
```

① Get current epoch time.

② Convert epoch time to human readable time in UTC.

③ Convert human readable time in UTC to epoch time.

If you want even nicer looking date/time strings, you should check out Java's SimpleDateFormat class.

Chapter 26. Shell

`org.arl.fjage.shell.Services.SHELL`

The SHELL service provides a way to run commands and access files on a node. It is used by agents providing the REMOTE service to support remote execution of commands from other nodes.

26.1. Overview

Agents providing the SHELL service support execution of commands, and access to files on the node. While shell agents typically provide interactivity using a terminal/console, they also support messages for other agents to request execution of commands or access to files.

26.1.1. Messages

- `ShellExecReq` ⇒ `AGREE` / `REFUSE` / `FAILURE` — execute a command
- `GetFileReq` ⇒ `FileGetRsp` / `REFUSE` / `FAILURE` — read a file or directory contents
- `PutFileReq` ⇒ `AGREE` / `REFUSE` / `FAILURE` — write contents to a file, or delete a file

26.2. Script engines

The language in which the commands are written is not defined by the service, but depends on the shell agent. fjåge supports a pluggable mechanism for an `ShellAgent` to use any `ScriptEngine`. Various script engines are available in fjåge and UnetStack, including the `GroovyScriptEngine`, `EchoScriptEngine`, and `ATScriptEngine`.

26.3. Examples

Start the 2-node network and connect to node A:

```
> agentsForService org.arl.fjage.shell.Services.SHELL                ①
[websh]
> websh.send new ShellExecReq(cmd: 'file("foobar").text = "FOOBAR";') ②
websh >> AGREE
> ls                                                                 ③
foobar [6 bytes]
README.md [759 bytes]
> file("foobar").text                                                ④
FOOBAR
```

① We find that `websh` is the agent that provides us the SHELL service.

② We send a command to `websh` to execute, and it agrees to do so. Since the commands we type are also executed by the `websh` agent, we need to be careful to not block the execution. Hence we use a `send` rather than a `request` (or equivalently `<<`).

③ The command was to create a `foobar` file, so we check that the file is created.

④ We read the contents of the `foobar` file to confirm that `FOOBAR` was correctly written to it.

Next, let's try the `GetFileReq` and `PutFileReq` messages to read, write and delete this file:

```
> websh.send new GetFileReq(filename: 'scripts/foobar')                ①
websh >> INFORM: GetFileRsp
> ntf.contents                                                         ②
[70, 79, 79, 66, 65, 82]
> new String(ntf.contents)                                             ③
FOOBAR
> websh.send new PutFileReq(filename: 'scripts/foobar', contents: 'fooooobaaaar')
websh >> AGREE                                                         ④
> file('foobar').text                                                  ⑤
fooooobaaaar
> websh.send new PutFileReq(filename: 'scripts/foobar', contents: null)
websh >> AGREE                                                         ⑥
> ls
README.md [759 bytes]
> websh.send new GetFileReq(filename: 'scripts')                       ⑦
websh >> INFORM: GetFileRsp
> new String(ntf.contents)
README.md       759     1568297372000                                  ⑧
```

① The file `foobar` was created in the `scripts` folder, which is the default location for the `file()` function. We ask to read the file, and get a `GetFileRsp` response back.

② The file contents are read back as a list of bytes.

③ We convert the list of bytes to a String to get our `FOOBAR` contents.

④ We send a `PutFileReq` to change the contents of the file.

⑤ We verify that the file contents were indeed changed, as requested.

⑥ Sending a `PutFileReq` with `contents` set to `null` deletes the file.

⑦ Asking for the contents of a directory using `GetFileReq` gets us the directory listing back.

⑧ The listing consists of all files in the directory, one file per line. Each line has a filename, file size and file modificiation timestamp (epoch time). If a file is a directory, the filename is suffixed by a `/`.

We interacted with the SHELL service provider using a shell! That's not very useful in practice, but served to show you how these messages work. Typically, these messages are sent by other agents that wish to get the shell to run commands and access files for them (e.g. `RemoteControl` agent in Section 23.2). The agents may be running remotely in a fjåge slave container or on a gateway (via the UnetSocket API), where they may not have direct access to the filesystem of the node.

Part V: Extending UnetStack

Chapter 27. Developing your own agents

By now, you should be very familiar with the concept of agents. You have interacted with them via commands and messages throughout this handbook, but what exactly is an agent?

If you lookup the Wikipedia entry for a software agent, you'll find:

> The term **agent** describes a software abstraction, an idea, or a concept, similar to object-oriented programming terms such as methods, functions, and objects. The concept of an agent provides a convenient and powerful way to describe a complex software entity that is capable of acting with a certain degree of autonomy in order to accomplish tasks on behalf of its host. But unlike objects, which are defined in terms of methods and attributes, an agent is defined in terms of its behavior.
>
> — Wikipedia: Software agent, retrieved 8 September 2019

In this chapter, we take this somewhat abstract concept and crystallize it by developing a simple agent. While the idea of writing your own agent might sound daunting at first, you'll soon see that it is actually quite easy!

27.1. Unet agents

Agents are the basic building blocks of the UnetStack. They exchange messages, provide services and implement protocols. While what is expected from a well-behaved agent is quite demanding, most of the necessary core behaviors are already implemented for you by the `UnetAgent` base class. All you need to do is to extend it, and add in a little code to teach the agent what you want it to do.

While you have the option of writing agents in Java or Groovy (or any other language running on the Java VM), we recommend writing agents in Groovy, as Groovy agents tend to need less biolerplate code and are more readable and maintainable. They are also easier to test as Groovy classes can be dynamically loaded from source, without having to pre-compile them. However, if you are already an expert in Java and prefer to use it, you're welcome to do so.

The basic skeleton of a Groovy agent looks like this:

```
import org.arl.fjage.*
import org.arl.unet.*

class MyAgent extends UnetAgent {

  @Override
  void setup() {
    // this method is called when the stack is initialized
    // register services and capabilities that you provide here
  }

  @Override
  void startup() {
    // this method is called just after the stack is running
    // look up other agents and services here, as needed
    // subscribe to topics of interest to get notifications
  }

  @Override
  Message processRequest(Message msg) {
    // process requests supported by the agent, and return responses
    // if request is not processed, return null
    return null
  }

  @Override
  void processMessage(Message msg) {
    // process other messages, such as notifications here
    // if a message is not interesting, it can be safely just ignored
  }

}
```

While you don't strictly need the `@Override` annotations, it is a good practice to use them whenever you are overriding a method from a superclass. The annotation tells the compiler that this is what you intend, and so if you make a typographical mistake and type in a wrong method name (one that doesn't exist in the superclass), the compiler will warn you.

If you do not need any of these methods, you can skip the definition as the base class provides default implementations. There are a several other methods that you can override to customize your agent, but these are less commonly needed and so we'll skip them for now. You'll come across them later.

If you happen to be already familiar with the fjåge agent lifecycle, you may wish to note that the `setup()` method is called from the `init()` method of the agent. The `startup()` method is called from a one-shot behavior scheduled during initialization. The `processRequest()` and `processMessage()` methods are called from a message behavior added during initialization.

27.2. Groovy echo daemon

It's best to illustrate with a simple example.

Let's develop an *echo daemon* that will respond to each incoming *echo request* datagram with an *echo response* datagram containing the same data as the echo-request. We need a way to identify which

datagram is an echo request, as we don't want to be echoing datagrams intended for other agents or for the user. We do this by defining an echo request datagram as any datagram with protocol `USER` (recall that protocol numbers from `USER` onwards are available for your own applications to use). We do not want to use the response to use the same protocol, otherwise our daemon (running on the source node) could get confused and echo the response, which would in turn be echoed again by the destination node's daemon, ad infinitum. So we use protocol `DATA` for the echo response datagram, as this protocol is intended by generic application data.

Here's our daemon:

```
import org.arl.fjage.*
import org.arl.unet.*

class EchoDaemon extends UnetAgent {

  @Override
  void startup() {
    // subscribe to all agents that provide the datagram service
    subscribeForService(Services.DATAGRAM)
  }

  @Override
  void processMessage(Message msg) {
    if (msg instanceof DatagramNtf && msg.protocol == Protocol.USER) {
      // respond to protocol USER datagram with protocol DATA datagram
      send new DatagramReq(
        recipient: msg.sender,
        to: msg.from,
        protocol: Protocol.DATA,
        data: msg.data
      )
    }
  }

}
```

Let's walk through the above code:

1. Our agent does not provide any formal services or capabilities, so we we skip the `setup()` and `processRequest()` methods from the skeleton.
2. The `startup()` method looks up all agents providing the DATAGRAM service, and subscribes to any notifications from any of these agents. These notifications will inlcude the `DatagramNtf` messages that are published when datagrams are received from another node. When a notification arrives, the `processMessage()` method will be called.
3. In the `processMessage()` method, we check for datagram notifications with protocol `USER`, and respond to each of them by sending a `DatagramReq` to the sender of the notification, requesting it to send a datagram with protocol `DATA` to the node that sent the echo request, with the data copied from the echo request.

That's it!

Do not get confused between `sender` and `from`, and `recipient` and `to` fields in datagram messages. The `sender` and `recepient` **always** refer to the agents that generate and consume the message. These are entities within a single Unet node. The `from` and `to` are node addresses that tell us which node is transmitting the datagram, and which node is the intended destination.

It's time for us to test this agent. Create a file called `EchoDaemon.groovy` in the `classes` folder and copy the above daemon code into it.

Editing scripts and classes

With the unet simulator or unet audio running on your machine, you can use your favorite text editor to directly create the `EchoDaemon.groovy` in the `classes` folder. However, a more generic way (that works on modems as well) is to open node A's shell, select `Script editor`, and use the new file button () in the `/classes/` section to create the file:

The same approach can be used to create Groovy scripts in the `scripts` folder.

Now start the 2-node network simulation that we have been using as a testbed, and on node B, load the agent:

```
> container.add 'echo', new EchoDaemon();            ①
> ps
remote: org.arl.unet.remote.RemoteControl - IDLE
state: org.arl.unet.state.StateManager - IDLE
rdp: org.arl.unet.net.RouteDiscoveryProtocol - IDLE
ranging: org.arl.unet.phy.Ranging - IDLE
uwlink: org.arl.unet.link.ECLink - IDLE
node: org.arl.unet.nodeinfo.NodeInfo - IDLE
websh: org.arl.fjage.shell.ShellAgent - RUNNING
simulator: org.arl.unet.sim.SimulationAgent - IDLE
phy: org.arl.unet.sim.HalfDuplexModem - IDLE
bbmon: org.arl.unet.bb.BasebandSignalMonitor - IDLE
arp: org.arl.unet.addr.AddressResolution - IDLE
transport: org.arl.unet.transport.SWTransport - IDLE
echo: EchoDaemon - IDLE                            ②
router: org.arl.unet.net.Router - IDLE
mac: org.arl.unet.mac.CSMA - IDLE
WebGW-5c9c1c68385a388f: REMOTE
```

① Create an agent called `echo` based on the `EchoDaemon` class.

② We see that the `echo` agent is now running.

Our daemon is up and running!

Debugging agents

If you have any errors in the `EchoDaemon.groovy` that cause compilation to fail, the agent won't load, and you'll get an error message on the shell. Sometimes it helps to look at the log file (`logs/log-0.txt`) for more details on the error.

In some rare cases, instead of printing an error, the shell may simply refuse to run the command by showing a "-" and waiting for more input because it thinks that the command you gave is incomplete. If this happens, look at your code to find the error, or try compiling manually using `groovyc` (similar to `javac` command in the next section) to get more details on the error.

Once the daemon is successfully loaded on node B, we can test it from node A:

```
> subscribe phy                                          ①
> phy << new DatagramReq(to: host('B'), protocol: Protocol.USER, data: [42]) ②
AGREE
phy >> TxFrameNtf:INFORM[type:DATA txTime:2809812247]
phy >> RxFrameStartNtf:INFORM[type:DATA rxTime:2811767943]
phy >> RxFrameNtf:INFORM[type:DATA from:31 to:232 rxTime:2811767943 (1 byte)]
> ntf.data
[42]                                                     ③
```

① We subscribe to `phy` so that we can see the incoming echo response from the peer node.

② Transmit a physical layer frame containing the echo request and some data.

③ The data we sent was echoed back.

We have written our first agent! Was easy, wasn't it?

Unet modems also have a `classes` folder that accepts Groovy source files or compiled Java/Groovy class files. You can use the web interface of the modem to upload files to that folder. If your code has many class files, you may wish to package them together into a jar archive and place it in the `jars` folder.

27.3. Java echo daemon

If you're a Java programmer and find the Groovy syntax daunting, you might prefer to write your agents in pure Java (at the expense of verbosity and more steps for testing). This is the equivalent Java code below for the Groovy agent we developed in the last section:

```
import org.arl.fjage.*;
import org.arl.unet.*;

public class EchoDaemon extends UnetAgent {

  @Override
  public void startup() {
    // subscribe to all agents that provide the datagram service
    subscribeForService(Services.DATAGRAM);
  }

  @Override
  public void processMessage(Message msg) {
    if (msg instanceof DatagramNtf && ((DatagramNtf)msg).getProtocol() == Protocol.USER) {
      // we got an echo request!
      // respond with a protocol DATA datagram
      DatagramNtf ntf = (DatagramNtf)msg;
      DatagramReq req = new DatagramReq(ntf.getSender());
      req.setTo(ntf.getFrom());
      req.setProtocol(Protocol.DATA);
      req.setData(ntf.getData());
      send(req);
    }
  }

}
```

In Java, you'll first need to compile the Java code. Create a `EchoDaemon.java` file with the above contents. To compile it, you'll need to have fjåge and unet-framework jar files on the classpath:

```
$ javac -cp lib/fjage-1.6.jar:lib/unet-framework-3.0-beta.jar EchoDaemon.java
```

You should now have a `EchoDaemon.class` file which you copy to the `classes` folder. To avoid duplicate classes, remember to first delete the `EchoDaemon.groovy` file!

Finally, you can run the 2-node network simulator and test the agent, just as you did in the previous section.

27.4. Behaviors

Agents implement most of their functionality with behaviors.

UnetStack is implemented on top of the fjåge agent framework. fjåge provides a set of standard behaviors for agents to extend. We will explore some of these behaviors in this section, but encourage you to read the fjåge documentation at your leisure to learn more.

We have been implicitly using two behaviors so far. The `startup()` method is called by the `UnetAgent` base class using a `OneShotBehavior`, and the `processMessage()` method is called from a `MessageBehavior`. While you could have manually added these behaviors, the `UnetAgent` base class does this for you, because almost all unet agents require this.

Let's next look at a use case for explicitly adding other behaviors. Say we wanted our echo daemon to

not respond immediately, but after 7 seconds. How would we do that?

We could of course add a `delay(7000)` in the `processMessage()` method, but that would be a bad idea. If we did that, the agent would sleep for 7 seconds on receiving a request and not process any request from any other nodes! We want the agent to be responsive while waiting, and so do not want to block execution. Instead, we want a behavior that will occur 7 seconds later — this is precisely what a `WakerBehavior` does. Here's our new `processMessage()` method:

```
@Override
void processMessage(Message msg) {
  if (msg instanceof DatagramNtf && msg.protocol == Protocol.USER) {
    // respond to protocol USER datagram with protocol DATA datagram after 7 seconds
    add new WakerBehavior(7000, {
      send new DatagramReq(
        recipient: msg.sender,
        to: msg.from,
        protocol: Protocol.DATA,
        data: msg.data
      )
    })
  }
}
```

The `WakerBehavior` that we add is triggered 7000 ms later, and the echo response is sent in that behavior. Simple!

Behaviors in Groovy use closures to make the syntax easy to work with. If you were writing your agent in Java, you'd need to create an anonymous class and override the `onWake()` method.

Go ahead and replace the `processMessage()` method in your `EchoDaemon.groovy` file and try it! In order to reload the agent, all you need to do on node B is:

```
> container.kill echo
true
> container.add 'echo', new EchoDaemon();
```

And now you can send an echo request from node A as before and see that the response is delayed by 7 seconds.

You could also send a second request during those 7 seconds, and the echo daemon on node B would process that concurrently. You can send 2 echo requests right after each other, and you'll see the corresponding echo responses 7 seconds later, but right after each other.

fjåge behaviors

fjåge provides several behaviors that are commonly used in unet agents:

One-shot behavior

A behavior that is run only once at the earliest opportunity.

Cyclic behavior

A cyclic behavior is run repeatedly as long as it is active. The behavior may be blocked and restarted as necessary.

Waker behavior

A behavior that is run after a specified delay in milliseconds.

Ticker behavior

A behavior that runs repeatedly with a specified delay between invocations.

Backoff behavior

A behavior that is similar to the waker behavior, but allows the wakeup time to be extended dynamically. This is typically useful to implement backoff or retry timeouts.

Poisson behavior

A behavior that is similar to a ticker behavior, but the interval between invocations is an exponentially distributed random variable. This simulates a Poisson arrival process, commonly used to model network data sources.

Finite state machine behavior

Finite state machines are commonly used to implement network protocols. They can easily be implemented using this behavior. These machines are composed out of multiple states, each of which is like a cyclic behavior, with state transitions that can be triggered by the component behaviors.

You can read more about these behaviors in the fjåge documentation on Agents & Behaviors.

27.5. Parameters

We have seen many agents with parameters that you can get/set. If we wanted to make our echo daemon delay configurable, it would be perfect to expose it as a parameter. Let's do that next.

With the echo daemon loaded on node B, we see that it doesn't have any configurable parameters by default:

```
> echo
<<< EchoDaemon >>>
```

Let's add a title, description and one `delay` parameter to our daemon:

```
import org.arl.fjage.*
import org.arl.unet.*

class EchoDaemon extends UnetAgent {

  enum Params implements Parameter {        ①
    delay
  }

  final String title = 'Echo Daemon'        ②
  final String description = 'Echoes any USER datagrams back as DATA' ③

  int delay = 7000                          ④

  @Override
  void startup() {
    // subscribe to all agents that provide the datagram service
    subscribeForService(Services.DATAGRAM)
  }

  @Override
  void processMessage(Message msg) {
    if (msg instanceof DatagramNtf && msg.protocol == Protocol.USER) {
      // respond to protocol USER datagram with protocol DATA datagram after 7 seconds
      add new WakerBehavior(delay, {
        send new DatagramReq(
          recipient: msg.sender,
          to: msg.from,
          protocol: Protocol.DATA,
          data: msg.data
        )
      })
    }
  }

  List<Parameter> getParameterList() {      ⑤
    allOf(Params)
  }

}
```

① Declare a list of parameters that the agent advertises. We have declared this enum as an inner class, but you could choose to declare it as a separate class if you wish.

② Provide a descriptive title for the agent.

③ Provide a descriptive text for the agent.

④ Declare the parameter.

⑤ Advertise the list of parameters.

Note that we had to take 3 steps to add a parameter: declare a list of parameters, declare the parameter, and advertise the parameter. While this might seem like a lot, bear in mind that parameters are much more than just agent's class attributes. Parameters can be get/set remotely, even from a different Java VM, different computer, or through a UnetSocket gateway API.

If you were writing the agent in Java instead of Groovy, you'd need to getters and setters for parameter `delay`, rather than simply declare the attribute. This is because Groovy automatically creates the getters and setters for you.

Let's see how the agent looks with parameters. Reload the agent on node B and check its parameters:

```
> container.kill agent('echo')
true
> container.add 'echo', new EchoDaemon();
> echo
<<< Echo Daemon >>>                      ①

Echoes any USER datagrams back as DATA   ②

[EchoDaemon.Params]
  delay = 7000

> echo.delay
7000
> echo.delay = 5000
5000
> echo.delay
5000
```

① Notice the change in title.

② The description is shown here.

We have changed the delay from 7 seconds to 5 seconds. Go ahead and send a echo request from node A and see that you get a response back in 5 seconds!

If you want to compute parameter values on demand or validate parameters, you can implement getters/setters for the parameter, and they will be called. If you want a read-only parameter, you can declare the attribute as `private` and implement only a getter for that parameter.

While our example above uses a static description, the description can also be dynamic. This can be useful if you want to display agent's status information in the description. To implement dynamic descriptions, simply replace the `description` attribute by a getter `getDescription()` that returns a `String` description when called.

27.6. Services, capabilities and notifications

Most of the agents we have been interacting with advertised services, and sometimes optional capabilities. They also honor requests and publish unsolicited notifications. All of these are quite straightforward to implement, and you can explore some of these features in this blog article on how to implement a simple PHYSICAL service agent (modem driver). We will explore some of these in the next chapter, along with other cool features like finite state machine behaviors and protocol data unit (PDU) codecs.

Chapter 28. Implementing network protocols

You now know how to write simple agents. But real world network protocols demand more complexity such as advertising services, looking up other agents, providing parameters that are computed on demand, encoding/decoding complex PDUs, generating random variates, and describing behaviors as finite state machines (FSMs). In this chapter, we illustrate how to do all these things with ease, using a few examples.

In Chapter 19, we looked at the MAC service in detail. In the next few sections, we develop three simple MAC agents (`MySimplestMac`, `MySimpleThrottledMac` and `MySimpleHandshakeMac`) to illustrate how network protocols and services are implemented by agents. The MAC agents are intentionally kept simple and not optimized for performance, as we wish to illustrate the key aspects of MAC agent development without getting lost in the details of optimal protocols.

28.1. Simple MAC without handshake

To illustrate how a MAC agent might work, let us start with a simple MAC agent that grants every reservation request as soon as it is made:

```
import org.arl.fjage.*
import org.arl.unet.*
import org.arl.unet.mac.*

class MySimplestMac extends UnetAgent {

  @Override
  void setup() {
    register Services.MAC               // advertise that the agent provides a MAC service
  }

  @Override
  Message processRequest(Message msg) {
    if (msg instanceof ReservationReq) {

      // check requested duration
      if (msg.duration <= 0) return new RefuseRsp(msg, 'Bad reservation duration')

      // prepare START reservation notification
      ReservationStatusNtf ntf1 = new ReservationStatusNtf(
        recipient: msg.sender,
        inReplyTo: msg.msgID,
        to: msg.to,
        status: ReservationStatus.START)

      // prepare END reservation notification
      ReservationStatusNtf ntf2 = new ReservationStatusNtf(
        recipient: msg.sender,
        inReplyTo: msg.msgID,
        to: msg.to,
        status: ReservationStatus.END)

      // send START reservation notification immediately
      add new OneShotBehavior({
        send ntf1
      })

      // wait for reservation duration, and then send END reservation notification
      add new WakerBehavior(Math.round(1000*msg.duration), {
        send ntf2
      })

      // return a reservation response, which defaults to an AGREE performative
      return new ReservationRsp(msg)
    }
    return null
  }

}
```

Note a number of interesting features of the code above:

1. The `setup()` method is used to advertise the service provided by this agent.
2. We provide basic error checking, and refuse a request that is invalid, providing a descriptive reason.
3. We prepare the AGREE response as well as the START and END status notification messages, all at once. We send out the START notification immediately (using a `OneShotBehavior`), use a `WakerBehavior` to schedule the END notification to be sent out at an appropriate time, and then simply return the AGREE response. The use of the `OneShotBehavior` ensures that the START notificaion is sent after the

AGREE response, and not before.

4. We return a `null` if we don't understand the request, allowing the superclass to respond with a NOT_UNDERSTOOD message.

While the above code implements a fully functional MAC agent, it needs to respond to `ReservationCancelReq`, `ReservationAcceptReq` and `TxAckReq` messages, and provide `channelBusy`, `reservationPayloadSize`, `ackPayloadSize`, `maxReservationDuration` and `recommendedReservationDuration` parameters in order to comply with the MAC service specification (Chapter 19). We add this functionality trivially, by responding to the messages with `RefuseRsp` (message with a `REFUSE` performative and a descriptive reason), and returning default values for all the parameters. The resulting complete source code is shown below:

```
import org.arl.fjage.*
import org.arl.unet.*
import org.arl.unet.mac.*

class MySimplestMac extends UnetAgent {

  @Override
  void setup() {
    register Services.MAC
  }

  @Override
  Message processRequest(Message msg) {
    switch (msg) {
      case ReservationReq:
        if (msg.duration <= 0) return new RefuseRsp(msg, 'Bad reservation duration')
        ReservationStatusNtf ntf1 = new ReservationStatusNtf(
          recipient: msg.sender,
          inReplyTo: msg.msgID,
          to: msg.to,
          status: ReservationStatus.START)
        ReservationStatusNtf ntf2 = new ReservationStatusNtf(
          recipient: msg.sender,
          inReplyTo: msg.msgID,
          to: msg.to,
          status: ReservationStatus.END)
        add new OneShotBehavior({
          send ntf1
        })
        add new WakerBehavior(Math.round(1000*msg.duration), {
          send ntf2
        })
        return new ReservationRsp(msg)
      case ReservationCancelReq:
      case ReservationAcceptReq:                    // respond to other requests defined
      case TxAckReq:                                //  by the MAC service with a RefuseRsp
        return new RefuseRsp(msg, 'Not supported')
    }
    return null
  }

  // expose parameters defined by the MAC service, with just default values

  @Override
  List<Parameter> getParameterList() {
    return allOf(MacParam)                          // advertise the list of parameters
  }

  final boolean channelBusy = false                 // parameters are marked as 'final'
  final int reservationPayloadSize = 0              //  to ensure that they are read-only
  final int ackPayloadSize = 0
  final float maxReservationDuration = Float.POSITIVE_INFINITY
  final Float recommendedReservationDuration = null

}
```

Now we have a fully-compliant, but very simple, MAC agent!

28.2. Testing our simple MAC

The `MySimplestMac` agent from the previous section is available in the `samples` folder of your unet simulator. To test it, fire up the 2-node network simulator and connect to node A:

```
> ps
remote: org.arl.unet.remote.RemoteControl - IDLE
state: org.arl.unet.state.StateManager - IDLE
rdp: org.arl.unet.net.RouteDiscoveryProtocol - IDLE
ranging: org.arl.unet.phy.Ranging - IDLE
uwlink: org.arl.unet.link.ECLink - IDLE
node: org.arl.unet.nodeinfo.NodeInfo - IDLE
websh: org.arl.fjage.shell.ShellAgent - RUNNING
simulator: org.arl.unet.sim.SimulationAgent - IDLE
phy: org.arl.unet.sim.HalfDuplexModem - IDLE
bbmon: org.arl.unet.bb.BasebandSignalMonitor - IDLE
arp: org.arl.unet.addr.AddressResolution - IDLE
transport: org.arl.unet.transport.SWTransport - IDLE
router: org.arl.unet.net.Router - IDLE
mac: org.arl.unet.mac.CSMA - IDLE
```

We see that the `org.arl.unet.mac.CSMA` agent is running as the current `mac`. To use our `MySimplestMac` agent, you first need to kill the `org.arl.unet.mac.CSMA` agent, and then load the `MySimplestMac` agent:

```
> container.kill mac
true
> container.add 'mac', new MySimplestMac()
mac
> ps
remote: org.arl.unet.remote.RemoteControl - IDLE
state: org.arl.unet.state.StateManager - IDLE
rdp: org.arl.unet.net.RouteDiscoveryProtocol - IDLE
ranging: org.arl.unet.phy.Ranging - IDLE
uwlink: org.arl.unet.link.ECLink - IDLE
node: org.arl.unet.nodeinfo.NodeInfo - IDLE
websh: org.arl.fjage.shell.ShellAgent - RUNNING
simulator: org.arl.unet.sim.SimulationAgent - IDLE
phy: org.arl.unet.sim.HalfDuplexModem - IDLE
bbmon: org.arl.unet.bb.BasebandSignalMonitor - IDLE
arp: org.arl.unet.addr.AddressResolution - IDLE
transport: org.arl.unet.transport.SWTransport - IDLE
router: org.arl.unet.net.Router - IDLE
mac: MySimplestMac - IDLE

> mac
<<< MySimplestMac >>>

[org.arl.unet.mac.MacParam]
  ackPayloadSize = 0
  channelBusy = false
  maxReservationDuration = Infinity
  recommendedReservationDuration = null
  reservationPayloadSize = 0
```

It's loaded and working!

Now, you can ask for a reservation and see if it responds correctly:

```
> mac << new ReservationReq(to: 31, duration: 3.seconds)
ReservationRsp:AGREE
mac >> ReservationStatusNtf:INFORM[to:31 status:START]
mac >> ReservationStatusNtf:INFORM[to:31 status:END]
```

Indeed it does! The START notification arrives immediately after the AGREE response, and the END notification arrives about 3 seconds later.

Logging and debugging

When testing agents, you'll often feel the need to log debug information. Every agent already has a Java logger (`log`) defined, and can be used to log information to the log file (`logs/log-0.txt`). The Java logger supports various levels of logging: `severe`, `warning`, `info`, `fine`, `finer`, `finest`. For example, to log a message at a fine level, simply do something like:

```
log.fine 'Some debugging information'
```

The log level can be controlled on a per-class or per-package basis using the `logLevel` command on the unet shell (type `help logLevel` for details). To set the current log level to include fine level logs:

```
> logLevel FINE
```

You can access the logs from the web interface "Logs" tab, or on your disk in the `logs` folder. The active agent log file is always called `log-0.txt`. To see the last few lines of this file from your shell:

```
> tail
1568482567444|INFO|org.arl.unet.remote.RemoteControl/B@57:startup|Using transport for communication
1568482567447|INFO|org.arl.unet.link.ECLink/B@59:startup|No PHY specified, auto detecting...
1568482567448|INFO|org.arl.unet.link.ECLink/B@59:startup|Using agent 'phy' for PHY
1568482567448|INFO|org.arl.unet.link.ECLink/B@59:startup|No MAC specified, auto detecting...
1568482567449|INFO|org.arl.unet.link.ECLink/B@59:startup|Using agent 'mac' for MAC
1568482567451|INFO|org.arl.unet.transport.SWTransport/B@69:startup|Using router for communication
1568482567453|INFO|org.arl.unet.remote.RemoteControl/B@57:startup|Using websh for command exec
1568482567511|INFO|org.arl.unet.remote.RemoteControl/A@42:startup|Using websh for command exec
1568482572443|INFO|org.arl.unet.nodeinfo.NodeInfo/A@52:obtainAddress|Node name is A, address is 232,
address size is 8 bits
1568482572449|INFO|org.arl.unet.nodeinfo.NodeInfo/B@68:obtainAddress|Node name is B, address is 31,
address size is 8 bits
1568482584194|INFO|MySimplestMac/A@72:init|Loading agent mac [MySimplestMac] on A
```

28.3. Simple MAC with throttling

While the above simple MAC would work well when the traffic offered to it is random, it will perform poorly if the network is fully loaded. All nodes would constantly try to access the channel, collide and the throughput would plummet. To address this concern, one may add an exponentially distributed random backoff (Poisson arrival to match the assumption of Aloha) for every request to introduce randomness. The backoff could be chosen to offer a normalized network load of approximately 0.5, since this generates the highest throughput for Aloha.

Here's the updated code with some bells and whistles:

```
import org.arl.fjage.*
import org.arl.unet.*
import org.arl.unet.phy.*
import org.arl.unet.mac.*

class MySimpleThrottledMac extends UnetAgent {

  private final static double TARGET_LOAD     = 0.5
  private final static int    MAX_QUEUE_LEN   = 16

  ①
  private AgentID phy
  boolean busy = false   // is a reservation currently ongoing?
  Long t0 = null         // time of last reservation start, or null
  Long t1 = null         // time of last reservation end, or null
  int waiting = 0

  @Override
  void setup() {
    register Services.MAC
  }

  @Override
  void startup() {
    phy = agentForService Services.PHYSICAL      ②
  }

  @Override
  Message processRequest(Message msg) {
    switch (msg) {
      case ReservationReq:
        if (msg.duration <= 0) return new RefuseRsp(msg, 'Bad reservation duration')
        if (waiting >= MAX_QUEUE_LEN) return new RefuseRsp(msg, 'Queue full')
        ReservationStatusNtf ntf1 = new ReservationStatusNtf(
          recipient: msg.sender,
          inReplyTo: msg.msgID,
          to: msg.to,
          status: ReservationStatus.START)
        ReservationStatusNtf ntf2 = new ReservationStatusNtf(
          recipient: msg.sender,
          inReplyTo: msg.msgID,
          to: msg.to,
          status: ReservationStatus.END)

        // grant the request after a random backoff                        ③
        AgentLocalRandom rnd = AgentLocalRandom.current()                  ④
        double backoff = rnd.nextExp(TARGET_LOAD/msg.duration/nodes)       ⑤
        long t = currentTimeMillis()
        if (t0 == null || t0 < t) t0 = t
        t0 += Math.round(1000*backoff)  // schedule packet with a random backoff
        if (t0 < t1) t0 = t1            //   after the last scheduled packet ⑥
        long duration = Math.round(1000*msg.duration)
        t1 = t0 + duration
        waiting++
        add new WakerBehavior(t0-t, {           ⑦
          send ntf1
          busy = true
          waiting--
          add new WakerBehavior(duration, {
```

```
            send ntf2
            busy = false
          })
        })

        return new ReservationRsp(msg)
      case ReservationCancelReq:
      case ReservationAcceptReq:
      case TxAckReq:
        return new RefuseRsp(msg, 'Not supported')
    }
    return null
  }

  // expose parameters defined by the MAC service, and one additional parameter

  @Override
  List<Parameter> getParameterList() {
    return allOf(MacParam, Param)
  }

  enum Param implements Parameter {
    nodes                                          ⑧
  }

  int nodes = 6                          // number of nodes in network, to be set by user

  final int reservationPayloadSize = 0
  final int ackPayloadSize = 0
  final float maxReservationDuration = Float.POSITIVE_INFINITY

  boolean getChannelBusy() {                       ⑨
    return busy
  }

  float getRecommendedReservationDuration() {    ⑩
    return get(phy, Physical.DATA, PhysicalChannelParam.frameDuration)
  }

}
```

① We define a few attributes to keep track of channel state and reservation queue.

② We lookup other agents in `startup()` after they have had a chance to advertise their services during the setup phase.

③ Requests are no longer granted immediately, but after a random backoff instead.

④ Random numbers are generated using a `AgentLocalRandom` utility. This utility ensures repeatable results during discrete event simulation, aiding with debugging, and so is the preferred way of generating random variates.

⑤ The `nextExp()` function generate a exponentially distributed random number with a specified rate parameter. The rate parameter is computed such that the average backoff introduced helps to achieve the specified target load.

⑥ In Groovy, a comparison with `null` (initial value of `t1`) is permitted, and will always be false.

⑦ Note that we no longer send the START notification immediately. Instead we schedule it after a backoff, and then schedule the END notification after the reservation duration from the START.

⑧ We implement one user configurable parameter `nodes`, and advertise it.

⑨ Parameter `busy` is no longer always false, since we now keep track of reservations. We return `busy` to be true only during the time between a reservation START and END.

⑩ Parameter `recommendedReservationDuration` is now determined based on the frame duration of the PHYSICAL service, assuming that most reservations are for transmitting one frame. A client is free to choose a longer reservation time, if he wishes to transmit many frames in one go (as he should for efficient use of the channel).

A copy of this code is available in the `samples` folder of your unet simulator. We encourage you to test it out, in the same way as we tested `MySimplestMac` in Section 28.2. You'll find that the START notification no longer arrives immediately after the AGREE response, but arrives a few seconds later, after a random backoff.

28.4. Simple MAC with handshake

While the MAC agents we have developed so far are fully functional, they are simple, and do not involve any signaling for channel reservation. Many MAC protocols such as MACA and FAMA involve a handshake using RTS and CTS PDUs. To illustrate how more complex protocols are developed using UnetStack, we implement a simple RTS-CTS 2-way handshake-based MAC agent next.

Many communication protocols are best described using a FSM. We illustrate the FSM for our simple handshake-based MAC agent in Figure 9.

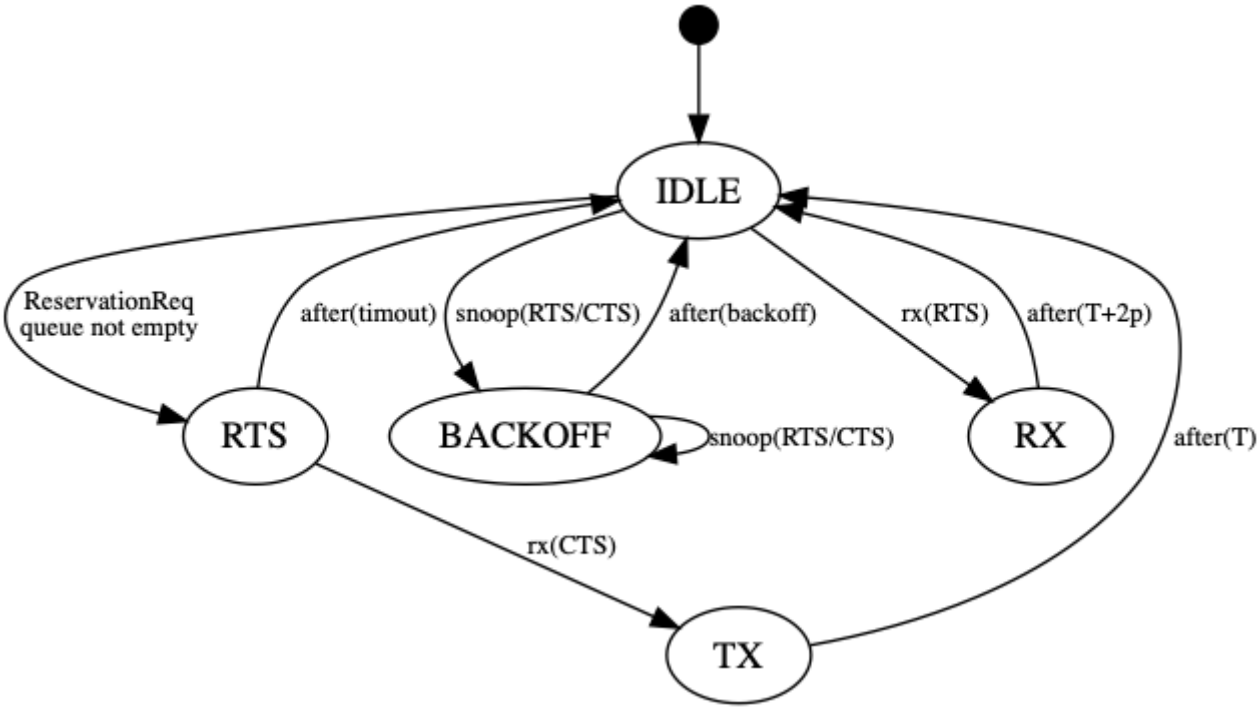


Figure 9. Finite state machine (FSM) for the simple handshake-based MAC protocol.

When the channel is free, the agent is in an IDLE state. If the agent receives a `ReservationReq`, it switches to the RTS state and sends a RTS PDU to the intended destination node. If it receives a CTS PDU back, then it switches to a TX state and urges the client to transmit data via a `ReservationStatusNtf` with a START status. After the reservation period is over, the agent switches back to the IDLE state. If no CTS PDU is received in the RTS state for a while, the agent times out and returns to the IDLE state while informing the client of a reservation FAILURE.

If the agent receives a RTS PDU in the IDLE state, it switches to the RX state and responds with a CTS PDU. The node initiating the handshake may then transmit data for the reservation duration. After the duration (plus some allowance for 2-way propagation delay), the agent switches back to the IDLE state. If the agent overhears (aka snoops) RTS or CTS PDUs destined for other nodes, it switches to a BACKOFF state for a while. During the state, it does not initiate or respond to RTS PDUs. After the backoff period, it switches back to the IDLE state.

Our RTS and CTS PDUs are identified by a protocol number. Since we are implementing a MAC protocol, we choose to tag our PDUs using the protocol number reserved for MAC agents (`Protocol.MAC`). We also define some timeouts and delays that we will need to use:

```
int PROTOCOL = Protocol.MAC

float RTS_BACKOFF     = 2.seconds
float CTS_TIMEOUT     = 5.seconds
float BACKOFF_RANDOM  = 5.seconds
float MAX_PROP_DELAY  = 2.seconds
```

Communication protocols often use complicated PDU formats. UnetStack provides a `PDU` class to help encode/decode PDUs. Although the RTS and CTS PDUs have a pretty simple format, the PDU is still useful in defining the format clearly:

```
int RTS_PDU = 0x01
int CTS_PDU = 0x02

PDU pdu = PDU.withFormat {
  uint8('type')         // RTS_PDU/CTS_PDU
  uint16('duration')    // ms
}
```

Here we have defined a PDU with two fields – type (8 bit) and duration (16 bit). The type may be either of RTS_PDU or CTS_PDU, while the duration will specify the reservation duration in milliseconds. We will later use this `pdu` object to encode and decode these PDUs.

Encoding and decoding PDUs

Since encoding and decoding of PDUs is required in almost all protocol implementations, UnetStack provides a `PDU` class to help you with it. The `PDU` class provides a declarative syntax for describing the PDU format. Once you have the PDU format declared, encoding and decoding PDUs is simply a matter of calling the `encode()` and `decode()` methods.

This is best illustrated with an example that you can try on a shell:

```
> import java.nio.ByteOrder
> pdu = PDU.withFormat {
-    length(16)                    // 16 byte PDU
-    order(ByteOrder.BIG_ENDIAN)   // byte ordering is big endian
-    uint8('type')                 // 1 byte field 'type'
-    uint8(0x01)                   // literal byte 0x01
-    filler(2)                     // 2 filler bytes
-    uint16('data')                // 2 byte field 'data' as unsigned short
-    padding(0xff)                 // padded with 0xff to make 16 bytes
- };
> bytes = pdu.encode([type: 7, data: 42])
[7, 1, 0, 0, 0, 42, -1, -1, -1, -1, -1, -1, -1, -1, -1, -1]
> pdu.decode(bytes)
[data:42, type:7]
```

The PDU length is defined using the `length` declaration, and the byte order is defined with the `order` declaration. Supported fields include `uint8`, `int8`, `uint16`, `int16`, `uint32`, `int32`, `int64`, and `chars` (string). Fillers and paddings are defined with `filler` and `padding` declarations.

Now comes the heart of our MAC protocol implementation — the FSM shown in Figure 9. First we define the FSM states and the events that the FSM reacts to:

```
enum State {
  IDLE, RTS, TX, RX, BACKOFF
}

enum Event {
  RX_RTS, RX_CTS, SNOOP_RTS, SNOOP_CTS
}
```

Next we use the `FSMBuilder` utility class to construct a `FSMBehavior` from a declarative concise representation of the FSM.

The FSM states are defined using the `state(…)` declarations. The actions to take when entering/exiting a state are defined in the `onEnter`/`onExit` clauses. The behavior of the FSM in response to events are defined using the `onEvent(…)` clauses. Timers that operate in a state are defined using the `after(…)` clauses. Finally actions to take continuously while in a state are defined using the `action` clause.

Finite state machines (FSMs)

FSMs are very commonly used in network protocol development. Although fjåge provides a `FSMBehavior` that helps implement FSMs in agents, it can be tedious to set up. UnetStack provides a `FSMBuilder` to make setting up FSM behaviors in agents easy.

Here are the key steps in setting up the FSM:

1. Define the states and events in the FSM as `enum` declarations.
2. Build the `FSMBehavior` using `FSMBuilder.build`. In building the FSM, you should have a `state(…)` defined for each of your FSM states.
3. In each FSM state, define your actions, events and timers using the `action`, `onEnter`, `onExit`, `onEvent` and `after` clauses. Actions are continuously executed, like a `CyclicBehavior`, when the FSM is in the relevant state. You should call `block()` and `restart()` on the behavior to avoid busy loops when the FSM is idle. The `onEnter` and `onExit` clauses are triggered when the state is entered and exited respectively. Events are triggered when the `trigger()` method of the behavior is called and the FSM is in the specified state. Timers (`after`) are automatically triggered after the specified amount of time after the state is entered.
4. The `setNextState()` and `reenterState()` methods allow you to effect state transitions in your FSM.
5. For short-lived FSMs, the `terminate()` method should be called when the FSM behavior is completed and should be terminated.

It should be easy to see the direct mapping between the FSM diagram and the FSM code below:

```
int MAX_RETRY = 3
int MAX_QUEUE_LEN = 16

Queue<ReservationReq> queue = new ArrayDeque<ReservationReq>(MAX_QUEUE_LEN)

FSMBehavior fsm = FSMBuilder.build {

  int retryCount = 0
  float backoff = 0
  def rxInfo

  state(State.IDLE) {
    action {
      if (!queue.isEmpty()) {
        // add random backoff for each reservation to allow other nodes
        // a chance to reserve, especially in case of a heavily loaded network
        after(rnd(0, BACKOFF_RANDOM)) {
          setNextState(State.RTS)
        }
      }
      block()
    }
    onEvent(Event.RX_RTS) { info ->
      rxInfo = info
      setNextState(State.RX)
    }
    onEvent(Event.SNOOP_RTS) {
```

```
      backoff = RTS_BACKOFF
      setNextState(State.BACKOFF)
    }
    onEvent(Event.SNOOP_CTS) { info ->
      backoff = info.duration + 2*MAX_PROP_DELAY
      setNextState(State.BACKOFF)
    }
  }

  state(State.RTS) {
    onEnter {
      Message msg = queue.peek()
      def bytes = pdu.encode(
        type: RTS_PDU,
        duration: Math.ceil(msg.duration*1000))
      phy << new TxFrameReq(
        to: msg.to,
        type: Physical.CONTROL,
        protocol: PROTOCOL,
        data: bytes)
      after(CTS_TIMEOUT) {
        if (++retryCount >= MAX_RETRY) {
          sendReservationStatusNtf(queue.poll(), ReservationStatus.FAILURE)
          retryCount = 0
        }
        setNextState(State.IDLE)
      }
    }
    onEvent(Event.RX_CTS) {
      setNextState(State.TX)
    }
  }

  state(State.TX) {
    onEnter {
      ReservationReq msg = queue.poll()
      retryCount = 0
      sendReservationStatusNtf(msg, ReservationStatus.START)
      after(msg.duration) {
        sendReservationStatusNtf(msg, ReservationStatus.END)
        setNextState(State.IDLE)
      }
    }
  }

  state(State.RX) {
    onEnter {
      def bytes = pdu.encode(
        type: CTS_PDU,
        duration: Math.round(rxInfo.duration*1000))
      phy << new TxFrameReq(
        to: rxInfo.from,
        type: Physical.CONTROL,
        protocol: PROTOCOL,
        data: bytes)
      after(rxInfo.duration + 2*MAX_PROP_DELAY) {
        setNextState(State.IDLE)
      }
      rxInfo = null
    }
  }

  state(State.BACKOFF) {
```

```
    onEnter {
      after(backoff) {
        setNextState(State.IDLE)
      }
    }
    onEvent(Event.SNOOP_RTS) {
      backoff = RTS_BACKOFF
      reenterState()
    }
    onEvent(Event.SNOOP_CTS) { info ->
      backoff = info.duration + 2*MAX_PROP_DELAY
      reenterState()
    }
  }

}
```

Do note that the above FSM includes a couple of details that were missing from the FSM diagram. Firstly, we implement a random backoff before switching to the RTS state to minimize contention. Secondly, we implement a `retryCount` counter to check the number of times a single `ReservationReq` has been tried. If it exceeds `MAX_RETRY`, we discard it. Thirdly, we have a `backoff` variable that allows different backoff times for different occasions. The variable is set each time, just before the state is changed to `State.BACKOFF` or before the backoff state is re-entered.

The FSM uses a simple utility method to send out `ReservationStatusNtf` notifications:

```
void sendReservationStatusNtf(ReservationReq msg, ReservationStatus status) {
  send new ReservationStatusNtf(
    recipient: msg.sender,
    inReplyTo: msg.msgID,
    to: msg.to,
    from: addr,
    status: status)
}
```

Now the hard work is done. We initialize our agent by registering the MAC service, looking up and subscribing to the PHYSICAL service (to transmit and receive PDUs), looking up our own address using the NODE_INFO service, and starting the `fsm` behavior:

```
AgentID phy
int addr

void setup() {
  register Services.MAC
}

void startup() {
  phy = agentForService Services.PHYSICAL
  subscribe(phy)
  subscribe(topic(phy, Physical.SNOOP))
  add new OneShotBehavior({
    def nodeInfo = agentForService Services.NODE_INFO
    addr = get(nodeInfo, NodeInfoParam.address)
  })
  add(fsm)
}
```

Note that we subscribe to the `topic(phy, Physical.SNOOP)` in addition to `phy`. This allows us to snoop RTS/CTS PDUs destined for other nodes. Also note that the address lookup is performed in a `OneShotBehavior` to avoid having the agent to block while the node information agent is starting up.

Just like in the earlier MAC implementation, we have to respond to various requests defined by the MAC service specifications:

```
Message processRequest(Message msg) {
  switch (msg) {
    case ReservationReq:
      if (msg.to == Address.BROADCAST || msg.to == addr)
        return new RefuseRsp(msg, 'Reservation must have a destination node')
      if (msg.duration <= 0 || msg.duration > maxReservationDuration)
        return new RefuseRsp(msg, 'Bad reservation duration')
      if (queue.size() >= MAX_QUEUE_LEN)
        return new RefuseRsp(msg, 'Queue full')
      queue.add(msg)
      fsm.restart()    // tell fsm to check queue, as it may block if empty
      return new ReservationRsp(msg)
    case ReservationCancelReq:
    case ReservationAcceptReq:
    case TxAckReq:
      return new RefuseRsp(msg, 'Not supported')
  }
  return null
}
```

If we get a `ReservationReq`, we validate the attributes, add the request to our queue and return a `ReservationRsp`. For other requests that we do not support, we simply refuse them.

If we receive PDUs from the physical agent, they come as `RxFrameNtf` messages via the `processMessage()` method. For all PDUs with a protocol number that we use, we decode them. We trigger appropriate FSM events in response to RTS and CTS PDUs — RX_RTS and RX_CTS events for PDUs destined to us, and SNOOP_RTS and SNOOP_CTS events for PDUs that we overhear:

```
void processMessage(Message msg) {
  if (msg instanceof RxFrameNtf && msg.protocol == PROTOCOL) {
    def rx = pdu.decode(msg.data)
    def info = [from: msg.from, to: msg.to, duration: rx.duration/1000.0]
    if (rx.type == RTS_PDU)
      fsm.trigger(info.to == addr ? Event.RX_RTS : Event.SNOOP_RTS, info)
    else if (rx.type == CTS_PDU)
      fsm.trigger(info.to == addr ? Event.RX_CTS : Event.SNOOP_CTS, info)
  }
}
```

Finally, we expose the parameters required by the MAC service specification:

```
List<Parameter> getParameterList() {          // publish list of all exposed parameters
  return allOf(MacParam)
}

final int reservationPayloadSize = 0          // read-only
final int ackPayloadSize = 0                  // read-only
final float maxReservationDuration = 65.535   // read-only

boolean getChannelBusy() {                    // considered busy if fsm is not IDLE
  return fsm.currentState.name != State.IDLE
}

float getRecommendedReservationDuration() {   // recommended duration: one DATA packet
  return get(phy, Physical.DATA, PhysicalChannelParam.frameDuration)
}
```

We are done! You can find the full listing of the MySimpleHandshakeMac agent in Appendix A (and also in the samples folder of your unet simulator).

28.5. Testing our simple MAC with handshake

Let's try out this MAC. The steps are similar to Section 28.2, but since the handshake requires MAC to be running on all nodes, you will have to fire up the 2-node network and replace the default CSMA MAC with MySimpleHandshakeMac on both nodes (node A and node B):

```
> container.kill mac
true
> container.add 'mac', new MySimpleHandshakeMac();
> mac
<<< MySimpleHandshakeMac >>>

[org.arl.unet.mac.MacParam]
  ackPayloadSize = 0
  channelBusy = false
  maxReservationDuration = 65.535
  recommendedReservationDuration = 0.7
  reservationPayloadSize = 0
```

Since the handshaking involves exchange of PDUs between nodes, it is instructive to see the PDUs being exchanged by subscribing to phy. You can make a reservation request on node A:

```
> subscribe phy
> mac << new ReservationReq(to: 31, duration: 3.seconds)
ReservationRsp:AGREE
phy >> TxFrameStartNtf:INFORM[type:CONTROL txTime:3631928985 txDuration:950]
phy >> RxFrameStartNtf:INFORM[type:CONTROL rxTime:3634151681]
phy >> RxFrameNtf:INFORM[type:CONTROL from:31 to:232 protocol:4 rxTime:3634151681 (3 bytes)]
mac >> ReservationStatusNtf:INFORM[to:31 from:232 status:START]
mac >> ReservationStatusNtf:INFORM[to:31 from:232 status:END]
```

We see that a CTS is transmitted (TxFrameStartNtf), then a RTS is received from node B (RxFrameStartNtf and RxFrameNtf). The reservation starts as soon as the CTS is received, and it ends 3 seconds later. Exactly as we wanted!

Coming soon…

Part VI: Simulating underwater networks

Chapter 29. Writing simulation scripts

We have been using simulations throughout the handbook, to demonstrate and test commands, scripts and agents without having to set up a real Unet. But how exactly do we tell the simulator what we want to simulate?

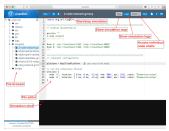
29.1. Integrated development environment

We have used the 2-node network simulation (`bin/unet samples/2-node-network.groovy`) umpteen times, but how did the simulator know where the nodes were and what agents were running on each node? That information must have been in the `2-node-network.groovy` simulation script, so let's take a look at that script next.

While we could open the script in our favorite editor directly, let's instead use the Unet IDE included with UnetStack, as it provides development tools that we will be needing in our journey. To start the Unet IDE:

```
$ bin/unet sim
Simulator IDE: http://localhost:8080/
```

This should open the IDE in your default browser:



The IDE provides you with a fairly common 3-panel layout, with a file browser in the left panel, a simulation shell at the bottom, and a file editor occupying most of the window. On the top, you see several buttons. The key buttons to node are the ▶ button that starts/stops simulations, the `Map` button that shows the current simulated nodes on a map, the 'Logs' button that allows you to view simulation logs, and a `Shells` dropdown that lists all the simulated nodes with shells. You can select any of the nodes from the list to connect to the shell of that node. The `Map` and `Shells` buttons are activated only once a simulation is running.

Load the `2-node-network.groovy` simulation script from the `samples` folder in the file editor. Then press ▶ to run it.

You can either press the ▶ button or type `sim.run 'samples/2-node-network.groovy'` to run the simulation from the simulation shell panel.

In the shell panel, you'll see:

```
2-node network
--------------

Node A: tcp://localhost:1101, http://localhost:8081/
Node B: tcp://localhost:1102, http://localhost:8082/
```

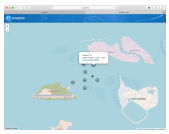
To access node A shell, either control-click the URL for node A shell (displayed on the simulation shell) or select `Node A (232)` from the `Shells` dropdown menu. This will open the node A shell in a separate browser tab. Once you have access to the shells for your node, you are on familiar ground, as you have been working with numerous realtime simulation in previous chapters. Now, you can safely close the shell tab for now and go back to the IDE tab. The shell tab can be reopened anytime you want.

Next, try out the `Map` button, and you'll see the 2 nodes in our simulation on a map:

This map doesn't look like much, with just 2 nodes 1 km apart on a blue background. The 2-node network simulation isn't geolocated, so the map doesn't have much to show. Let's stop this simulation by pressing the ■ button, and start the `scripts/mission2013-network.groovy` simulation instead.

You can either press the ■ button or type `sim.stop` in the simulation shell panel to stop the currently running simulation.

Now open the `Map`, and you'll get a much nicer map of the network deployed in southern Singapore waters:



Clicking on each individual node shows some information about that node, and provides a link to opening that node's shell (if it has a shell agent running). In case of mobile nodes (Section 29.5), you'll see the nodes moving on the map.

29.2. 2-node network

Now that we know how to use the IDE, let's stop the mission2013 network simulation and reopen the 2-node network simulation in the file browser. Recall that we started off the previous section wanting to study the `2-node-network.groovy` simulation script in detail to see how it works. So let's get down to it:

samples/2-node-network.groovy:

```
import org.arl.fjage.*                                          ①

////////////////////////////////////////////////////////////////////////////
// display documentation

println '''                                                     ②
2-node network
--------------

Node A: tcp://localhost:1101, http://localhost:8081/
Node B: tcp://localhost:1102, http://localhost:8082/
'''

////////////////////////////////////////////////////////////////////////////
// simulator configuration

platform = RealTimePlatform   // use real-time mode            ③

// run the simulation forever
simulate {                                                      ④
  node 'A', location: [ 0.km, 0.km, -15.m], web: 8081, api: 1101, stack: "$home/etc/setup"
  node 'B', location: [ 1.km, 0.km, -15.m], web: 8082, api: 1102, stack: "$home/etc/setup"
}
```

① Import classes needed in the simulation script.

② Display documentation.

③ Tell the simulator that we want to run in realtime mode.

④ Describe the simulation specifying nodes names 'A' and 'B', their locations, web interface port numbers, API port numbers and the default network stack to load on each node.

The simulation script is very simple. All it does is specify that we want to use the `RealTimePlatform` (since we want to run a realtime simulation), and then define the two nodes in the simulation. Node attributes such as node name, location, ports, and stack (agents to load) are specified when describing each node.

Let's next take a look at the `setup.groovy` script that describes the stack to load on each node:

etc/setup.groovy:

```
import org.arl.fjage.Agent

boolean loadAgentByClass(String name, String clazz) {
  try {
    container.add name, Class.forName(clazz).newInstance()
    return true
  } catch (Exception ex) {
    return false
  }
}

boolean loadAgentByClass(String name, String... clazzes) {
  for (String clazz: clazzes) {
    if (loadAgentByClass(name, clazz)) return true
  }
  return false
}

loadAgentByClass 'arp',       'org.arl.unet.addr.AddressResolution'
loadAgentByClass 'ranging',   'org.arl.unet.phy.Ranging'
loadAgentByClass 'mac',       'org.arl.unet.mac.CSMA'
loadAgentByClass 'uwlink',    'org.arl.unet.link.ECLink', 'org.arl.unet.link.ReliableLink'
loadAgentByClass 'transport', 'org.arl.unet.transport.SWTransport'
loadAgentByClass 'router',    'org.arl.unet.net.Router'
loadAgentByClass 'rdp',       'org.arl.unet.net.RouteDiscoveryProtocol'
loadAgentByClass 'state',     'org.arl.unet.state.StateManager'

container.add 'remote',       new org.arl.unet.remote.RemoteControl(cwd: new File(home, 'scripts'),
enable: false)
container.add 'bbmon',        new org.arl.unet.bb.BasebandSignalMonitor(new File(home, 'logs/signals-
0.txt').path, 64)
```

While this script might look complicated, what it does is quite simple. It loads the standard agents in the network stack. The complicated bits in the script are mostly to handle errors, if certain agents are unavailable (e.g. agents from the premium stack). We could use a much simpler script to load the stack, if we wanted to avoid this complexity:

Simpler etc/setup.groovy:

```
container.add 'arp',       new org.arl.unet.addr.AddressResolution()
container.add 'ranging',   new org.arl.unet.phy.Ranging()
container.add 'mac',       new org.arl.unet.mac.CSMA()
container.add 'uwlink',    new org.arl.unet.link.ReliableLink()
container.add 'transport', new org.arl.unet.transport.SWTransport()
container.add 'router',    new org.arl.unet.net.Router()
container.add 'rdp',       new org.arl.unet.net.RouteDiscoveryProtocol()
container.add 'state',     new org.arl.unet.state.StateManager()
container.add 'remote',    new org.arl.unet.remote.RemoteControl(cwd: new File(home, 'scripts'), enable:
false)
container.add 'bbmon',     new org.arl.unet.bb.BasebandSignalMonitor(new File(home, 'logs/signals-0.txt'
).path, 64)
```

This script just loads all the standard agents in the basic stack.

If you wanted to customize the stack in the simulation, you could specify a different script to setup the stack, or provide a closure directly when defining the simulation:

```
simulate {
  node 'A', location: [ 0.km, 0.km, -15.m], web: 8081, api: 1101, stack: "$home/scripts/custom.groovy"
  node 'B', location: [ 1.km, 0.km, -15.m], web: 8082, api: 1102, stack: {
    // only load 3 agents on node B
    container.add 'arp',       new org.arl.unet.addr.AddressResolution()
    container.add 'mac',       new org.arl.unet.mac.CSMA()
    container.add 'uwlink',    new org.arl.unet.link.ReliableLink()
  }
}
```

Recall that in Section 27.2, we developed our own `EchoDaemon.groovy` agent. If we wanted to preload it in our 2-node network simulation, we can add `container.add 'echo', new EchoDaemon()` in the `custom.groovy` script or directly in the closure shown above.

Simulated node properties

When defining a node, you can set many properties of the node:

`address`
: Node address.

`web`
: TCP/IP port number for the web interface. Each node should have a unique port number. By default, for security reasons, the web interface is only accessible from your local machine. If you wish for it to be accessible externally, you need to specify the `web` property as `['0.0.0.0', port]` where `port` is the port number.

`shell`
: If the value of `shell` is `true`, a console shell is opened on the node. No more than one node in the simulation should have a console shell. If the value of `shell` is numeric, it is treated as a TCP/IP port number to make the shell accessible over. Each node should have a unique port number. You can connect to the shell using `nc` or `telnet`.

`api`
: TCP/IP port number for the API port. This port is used by the gateway API or fjåge slave containers. Each node should have a unique port number.

`location`
: Node location specified as a 3-tuple. The format of the location tuple is described in Section 5.6.

`mobility`
: `true` if the node is mobile, `false` if it is static. The default is `false`, if `mobility` is not specified.

`heading`
: Initial heading of the node (in case of mobile nodes). The heading is specified in degrees, measured clockwise, north being 0.

`stack`
: Filename of script to run, or a closure to execute, to load agents in the network stack.

`model`
: Class to use for the NODE_INFO service. The NODE_INFO service for each node is normally provided by the `org.arl.unet.nodeinfo.NodeInfo` agent class. This agent is loaded before the stack is initialized, and therefore cannot be customized using the `stack` property.

29.3. Netiquette 3-node network

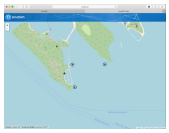
The `2-node-network.groovy` script defined 2 nodes that were 1 km apart, but were not geolocated. Recall from Section 5.6 that specifying a node origin allows us to geolocate the nodes on a map. The `netq-network.groovy` simulation script does this:

samples/netq-network.groovy:

```
import org.arl.fjage.RealTimePlatform

//////////////////////////////////////////////////////////////////////////////
// display documentation

println '''
Netiquette 3-node network
-------------------------

Node A: tcp://localhost:1101, http://localhost:8081/
Node B: tcp://localhost:1102, http://localhost:8082/
Node C: tcp://localhost:1103, http://localhost:8083/
'''

//////////////////////////////////////////////////////////////////////////////
// simulator configuration

platform = RealTimePlatform   // use real-time mode
origin = [1.216, 103.851]     ①

simulate {
  node 'A', location: [121.m,  137.m, -10.m], web: 8081, api: 1101, stack: "$home/etc/setup"
  node 'B', location: [160.m, -232.m, -15.m], web: 8082, api: 1102, stack: "$home/etc/setup"
  node 'C', location: [651.m,  140.m,  -5.m], web: 8083, api: 1103, stack: "$home/etc/setup"
}
```

① The specified `origin` (latitude, longitude) applies to all nodes in the simulation.

Starting the simulation and opening the map shows the nodes on the map, since the origin allows the IDE to geolocate the nodes:



The ✚ icon on the map marks the origin location.

29.4. Mission 2013 network

The simulation script is written in Groovy, so you can include complex logic in the script , if you wish. From this perspective, the `mission2013-network.groovy` script is instructive to look at:

samples/mission2013-network.groovy:

```
import org.arl.fjage.RealTimePlatform
import org.arl.unet.sim.channels.Mission2013a

//////////////////////////////////////////////////////////////////////////////
// display documentation

println '''
MISSION 2013 network
--------------------
'''
Mission2013a.nodes.each { addr ->
  println "Node $addr: tcp://localhost:${1100+addr}, http://localhost:${8000+addr}/"
}

//////////////////////////////////////////////////////////////////////////////
// simulator configuration

platform = RealTimePlatform   // use real-time mode
channel = [ model: Mission2013a ]                          ①
origin = [1.217, 103.743]

simulate {
  Mission2013a.nodes.each { addr ->                        ②
    node "$addr", location: Mission2013a.nodeLocation[addr], web: 8000+addr, api: 1100+addr, stack:
"$home/etc/setup"
  }
}
```

① The `channel` property of the simulation enables us to define details of the simulated physical channel for the network. We will learn more about simulating channels in Chapter 31.

② Nodes can be created programatically by iterating over the list of nodes defined in the `Mission2013a` class.

The `Mission2013a` class contains information about the MISSION 2013 experiment. The `mission2013-network.groovy` simulation script uses this information to create simulated nodes at the correct locations, and to define a channel model based on measurements during that experiment.

29.5. Node mobility

Nodes in a simulation may be mobile (e.g. autonomous underwater vehicles). Such nodes are motion models associated with them, to provide appropriate mobility during the simulation:

```
// AUV-1 moving in a straight line at constant speed
def n1 = node 'AUV-1', location: [0, 0, 0], mobility: true
n1.motionModel = [speed: 1.mps, heading: 30.deg]

// AUV-2 moving in a circle (constant speed, constant turn rate)
def n2 = node 'AUV-2', location: [0, 0, 0], mobility: true
n2.motionModel = [speed: 1.mps, turnRate: 1.dps]
```

We can also define more complex motion models:

```
// AUV-3 moving in a lawnmower pattern
def n3 = node 'AUV-3', location: [-20.m, -150.m, 0], heading: 0.deg, mobility: true
n3.motionModel = MotionModel.lawnmower(speed: 1.mps, leg: 200.m, spacing: 20.m, legs: 10)

// AUV-4 moving as defined below, using time or duration
def n4 = node 'AUV-4', location: [-50.m, -50.m, 0], mobility: true
n4.motionModel = [
  [time:     0.minutes, heading:  60.deg, speed:       1.mps],
  [time:     3.minutes, turnRate:  2.dps, diveRate:  0.1.mps],
  [time:     4.minutes, turnRate:  0.dps, diveRate:    0.mps],
  [time:     7.minutes, turnRate:  2.dps                    ],
  [time:     8.minutes, turnRate:  0.dps                    ],
  [duration: 3.minutes, turnRate:  2.dps, diveRate: -0.1.mps],
  [duration: 1.minute,  turnRate:  0.dps, diveRate:    0.mps]
]
```

We can even combine motion models:

```
def n5 = node 'AUV-5', location: [-20.m, -150.m, 0], heading: 0.deg, mobility: true

// dive to 30m before starting survey
n5.motionModel = [
  [duration: 5.minutes, speed: 1.mps, diveRate: 0.1.mps],
  [diveRate: 0.mps]
]

// then do a lawnmower survey
n5.motionModel += MotionModel.lawnmower(speed: 1.mps, leg: 200.m, spacing: 20.m, legs: 10)

// finally, come back to the surface and stop
n5.motionModel += [
  [duration: 5.minutes, speed: 1.mps, diveRate: -0.1.mps],
  [diveRate: 0.mps, speed: 0.mps]
]
```

Let's put AUVs 1-4 together into a single simulation script:

auv-network.groovy

```
import org.arl.fjage.RealTimePlatform
import org.arl.unet.sim.MotionModel

platform = RealTimePlatform

simulate {
    def n1 = node 'AUV-1', location: [0, 0, 0], mobility: true
    n1.motionModel = [speed: 1.mps, heading: 30.deg]
    def n2 = node 'AUV-2', location: [0, 0, 0], mobility: true
    n2.motionModel = [speed: 1.mps, turnRate: 1.dps]
    def n3 = node 'AUV-3', location: [-20.m, -150.m, 0], heading: 0.deg, mobility: true
    n3.motionModel = MotionModel.lawnmower(speed: 1.mps, leg: 200.m, spacing: 20.m, legs: 10)
    def n4 = node 'AUV-4', location: [-50.m, -50.m, 0], mobility: true
    n4.motionModel = [
        [time:     0.minutes, heading:  60.deg, speed:       1.mps],
        [time:     3.minutes, turnRate:  2.dps, diveRate:  0.1.mps],
        [time:     4.minutes, turnRate:  0.dps, diveRate:    0.mps],
        [time:     7.minutes, turnRate:  2.dps                    ],
        [time:     8.minutes, turnRate:  0.dps                    ],
        [duration: 3.minutes, turnRate:  2.dps, diveRate: -0.1.mps],
        [duration: 1.minute,  turnRate:  0.dps, diveRate:    0.mps]
    ]
}
```

Save this auv-network.groovy in your scripts folder and run it. Open the map, and watch your AUV nodes move!

Chapter 30. Discrete event simulation

Running simulations in realtime gives us an experience which is very similar to working with a real Unet, as we have seen in earlier chapters. This is very useful when you want to interact with the network manually, through a shell. However, as a network designer or protocol developer, you may sometimes need to run simulations to see how the network performs over days or months, and maybe run many such simulations, each with slightly different network settings or configuration. Doing this with a realtime simulator is impractical, as a realtime simulation would take days or months to run. The Unet simulator can be run in a *discrete event* mode, where the waiting time between events is *fast-forwarded* to yield results worth hours or days of real time within minutes. In this chapter, we explore how to use the disrete event mode for simulation of protocol performance.

30.1. ALOHA performance analysis

The *hello world* of the networking world is the ALOHA MAC protocol. The protocol is very simple: transmit a frame as soon as data arrives, without worrying about whether any other node is transmitting. While this behavior is straightforward to describe, simulating it accurately requires some thought.

Let's say we want to simulate a network with ALOHA MAC. On each node, we expect data to arrive randomly, with a known average arrival rate. The total number of data "chunks" arriving per unit time across the network is termed as *offered load*. As soon as a data chunk arrives, the node transmits it to a randomly chosen destination node (other than itself). The number of successfully delivered data chunks per unit time, across the entire network, is called the *throughput*. We are interested to study how the throughput varies as a function of offered load.

ALOHA has been extensively studied in literature, and its theoretical performance is well known. In order to simulate a network that can be compared against theory, we need to ensure that our simulation matches the assumptions made in the theoretical derivations:

1. The random arrival process follows a Poisson distribution.
2. If two frames arrive at a receiver with some overlap in time, they collide and are lost. Neither frame can be successfully decoded.
3. Each node is half-duplex, i.e., it cannot receive a frame while it is transmitting.
4. No frames are lost due to noise or channel effects such as multipath.
5. There is no propagation delay between nodes.

Assumptions 2 and 4 together form a model called the *protocol* channel model. We tell the simulator to adopt this model:

```
channel.model = ProtocolChannelModel
```

Underwater acoustic modems are usually half-duplex, and the default modem model in the simulator is the `HalfDuplexModem`, so we shouldn't need to do anything special for assumption 3. However, the `HalfDuplexModem` is smart enough to delay a transmission if another frame is being transmitted or received by the node, to avoid losing the other frame. While this is usually a good thing to do, it will

violate assumption 3 and give us results that don't agree with theory. To match the theoretical behavior, we have to stop any ongoing transmission or reception, when new data arrives for transmission:

```
phy << new ClearReq()                       // stop ongoing transmission/reception
phy << new TxFrameReq(to: dst, type: DATA)  // transmit a data frame to dst
```

The offered load and throughput are usually *normalized* by the number of frames that can be supported by the channel per unit time. By setting the frame duration to be one second, we ensure that the normalization factor is 1 (one packet can be transitted per second without collision). To do this, we set up the simulated modem to have no header/preamble overheads, and exactly 1 second worth of data that it can carry in a frame:

```
modem.dataRate = [2400, 2400].bps           // arbitrary data rate
modem.frameLength = [2400/8, 2400/8].bytes  // 1 second worth of data per frame
modem.headerLength = 0                      // no overhead from header
modem.preambleDuration = 0                  // no overhead from preamble
modem.txDelay = 0                           // don't simulate hardware delays
```

You can read more about `modem` models in Section 31.1.

A Poisson process (assumption 1) is easily simulated using the `PoissonBehavior` available in fjåge. Assumption 5 can also be easily met by placing all nodes at the same location.

Now let's put a first version of our script together to simulate a 4-node ALOHA network:

```
import org.arl.fjage.*
import org.arl.unet.*
import org.arl.unet.phy.*
import org.arl.unet.sim.*
import org.arl.unet.sim.channels.*
import static org.arl.unet.Services.*
import static org.arl.unet.phy.Physical.*

channel.model = ProtocolChannelModel        // use the protocol channel model
modem.dataRate = [2400, 2400].bps           // arbitrary data rate
modem.frameLength = [2400/8, 2400/8].bytes  // 1 second worth of data per frame
modem.headerLength = 0                      // no overhead from header
modem.preambleDuration = 0                  // no overhead from preamble
modem.txDelay = 0                           // don't simulate hardware delays

def nodes = 1..4                            // list with 4 nodes
def load = 0.2                              // offered load to simulate

simulate 2.hours, {                         // simulate 2 hours of elapsed time
  nodes.each { myAddr ->
    def myNode = node "${myAddr}", address: myAddr, location: [0, 0, 0]
    myNode.startup = {                      // startup script to run on each node
      def phy = agentForService PHYSICAL
      def arrivalRate = load/nodes.size()   // arrival rate per node
      add new PoissonBehavior(1000/arrivalRate, {     // avg time between events in ms
        def dst = rnditem(nodes-myAddr)     // choose destination randomly (excluding self)
        phy << new ClearReq()
        phy << new TxFrameReq(to: dst, type: DATA)
      })
    }
  }
}

// display collected statistics
println([trace.txCount, trace.rxCount, trace.offeredLoad, trace.throughput])
```

The script is easy to understand. In a 2-hour long simulation, we iterate over the list of nodes, and create each node at the origin. Each node adds a `PoissonBheavior` to generate random traffic at a rate corresponding to the offered `load` setting. The parameter of the Poisson behavior is the average time between events in milliseconds, which we compute based on the arrival rate. The destination for each transmission is randomly chosen from the list of nodes excluding the transmitting node. Once the simulation is completed, statistics are printed. The `trace` object is automatically defined by the simulator to collect typically required statistics.

The `rnditem(list)` function allows a random item to be chosen from a list. Other convenience functions related to random number generation include `rnd(min, max)` which generates a uniformly distributed random number between `min` and `max`, and `rndint(n)` which generates a uniformly distributed random number between `0` and `n-1`.

Open Unet IDE (`bin/unet sim`), create a new simulation script in the `scripts` folder, copy this code in, and run it. Within a few seconds, you should see the results:

```
[1398, 1080, 0.13631, 0.105]
1 simulation completed in 2.817 seconds
```

Since this is a Monte-Carlo simulation driven by a random number generator, the statistics you see will be similar, but not identical. A total of 1398 frames were transmitted, and 1080 of them were successfully received. The measured offered load was 0.136, and the throughput was 0.105.

Wondering why the measured offered load of 0.136 is a little less than the 0.2 that we intended? When two transmissions arrive with a very small delay, the earlier transmission is dropped when the next transmission begins. Only fully completed transmissions are counted by the `trace` statistics collector, and hence it sees a slightly lower load.

Hang on a minute! The simulation was meant to run for 2 hours, but it finished in less than 3 seconds!!

That's because we ran the simulation in a discrete event simulation mode (it is the default mode, if we don't set `platform = RealTimePlatform`). We could have explicitly set it (`platform = DiscreteEventSimulator`), if we wanted. Now that we can run hours worth of simulations in seconds, we can go ahead and measure ALOHA throughput at various load settings:

```
import org.arl.fjage.*
import org.arl.unet.*
import org.arl.unet.phy.*
import org.arl.unet.sim.*
import org.arl.unet.sim.channels.*
import static org.arl.unet.Services.*
import static org.arl.unet.phy.Physical.*

println '''
Pure Aloha simulation
====================

TX Count\tRX Count\tOffered Load\tThroughput
--------\t--------\t------------\t----------'''

channel.model = ProtocolChannelModel        // use the protocol channel model
modem.dataRate = [2400, 2400].bps           // arbitrary data rate
modem.frameLength = [2400/8, 2400/8].bytes  // 1 second worth of data per frame
modem.headerLength = 0                      // no overhead from header
modem.preambleDuration = 0                  // no overhead from preamble
modem.txDelay = 0                           // don't simulate hardware delays

def nodes = 1..4                            // list with 4 nodes
trace.warmup = 15.minutes                   // collect statistics after a while

for (def load = 0.1; load <= 1.5; load += 0.1) {

  simulate 2.hours, {                       // simulate 2 hours of elapsed time
    nodes.each { myAddr ->
      def myNode = node "${myAddr}", address: myAddr, location: [0, 0, 0]
      myNode.startup = {                    // startup script to run on each node
        def phy = agentForService PHYSICAL
        def arrivalRate = load/nodes.size() // arrival rate per node
        add new PoissonBehavior(1000/arrivalRate, {   // avg time between events in ms
          def dst = rnditem(nodes-myAddr)   // choose destination randomly (excluding self)
          phy << new ClearReq()
          phy << new TxFrameReq(to: dst, type: DATA)
        })
      }
    }
  } // simulate

  // tabulate collected statistics
  println sprintf('%6d\t\t%6d\t\t%7.3f\t\t%7.3f',
    [trace.txCount, trace.rxCount, trace.offeredLoad, trace.throughput])

} // for
```

Other than the pretty printing to tabulate the output, you'll see that we have added a `trace.warmup` time. This is to ensure that we only collect statistics after the simulation has reached steady state (in this case, after 15 minutes of simulation time).

A slightly beautified copy of the above code is available in the `samples/aloha.groovy` script. You can either run that, or run the above code. You should see something like this output:

```
Pure Aloha simulation
=====================

TX Count        RX Count        Offered Load    Throughput
--------        --------        ------------    ----------
   614             525           0.068           0.058
  1228             962           0.137           0.107
  1871            1249           0.209           0.139
  2480            1407           0.277           0.156
  3093            1535           0.347           0.171
  3759            1616           0.421           0.180
  4273            1665           0.479           0.183
  4971            1599           0.558           0.178
  5540            1605           0.622           0.178
  6256            1532           0.702           0.170
  6940            1375           0.783           0.153
  7338            1407           0.826           0.156
  7992            1338           0.904           0.149
  8598            1282           0.972           0.142
  9394            1048           1.062           0.116

15 simulations completed in 102.494 seconds
```

As expected from the ALOHA protocol, the maximum throughput of about 0.18 is reached at an offered load of about 0.5. We plot this against the theoretical ALOHA performance curve (`y = x exp(-2x)`) in Figure 10.

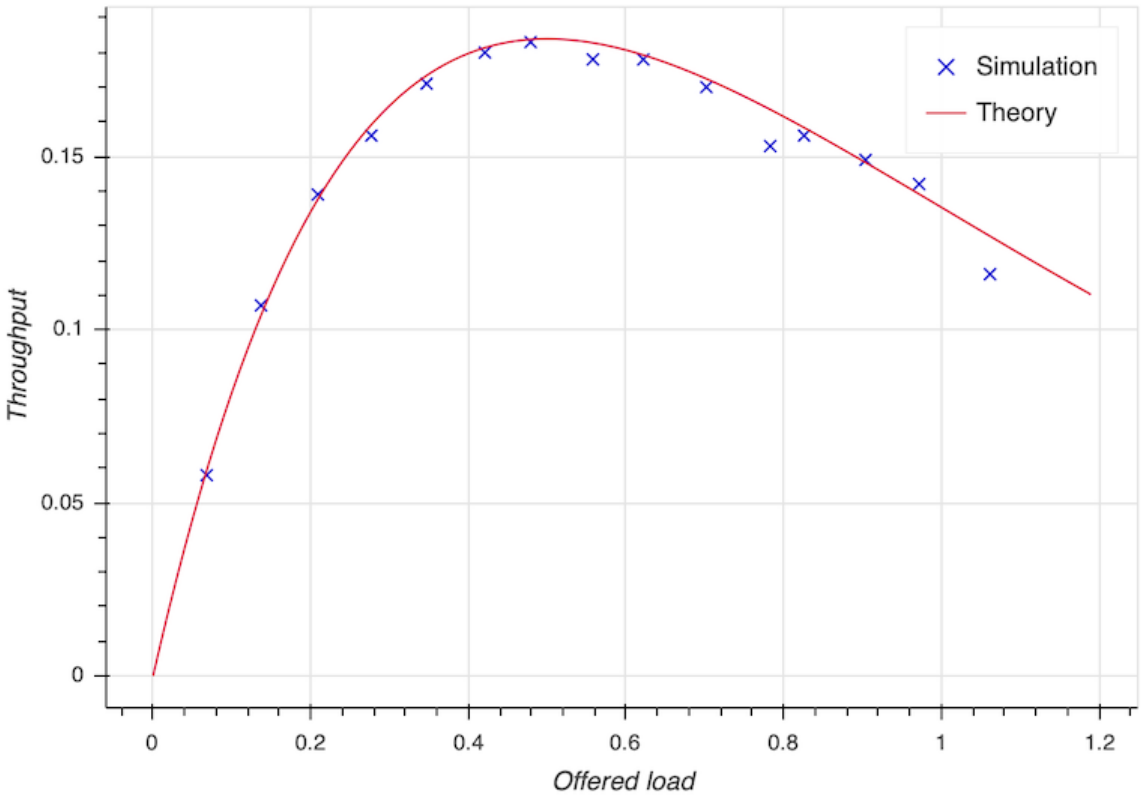


Figure 10. Simulated and theoretical ALOHA performance.

30.2. Logs, traces and statistics

When a simulation is run, usually two files are produced.

30.2.1. Log file

The `logs/log-0.txt` file contains detailed text logs from the Java logging framework. Your agents and simulation scripts may log additional information to this file using `log.info()` or `log.fine()` methods. This provides a flexible and customizable way to log events in your simulation for later analysis.

A typical extract of the log file is shown below:

```
1569242004546|INFO|org.arl.unet.nodeinfo.NodeInfo@558:setAddress|Node address changed to 1
1569242004548|INFO|Script1@558:invoke|Created static node 1 (1) @ [0, 0, 0]
1569242004552|INFO|org.arl.unet.nodeinfo.NodeInfo@558:setAddress|Node address changed to 2
1569242004553|INFO|Script1@558:invoke|Created static node 2 (2) @ [0, 0, 0]
1569242004553|INFO|org.arl.unet.nodeinfo.NodeInfo@558:setAddress|Node address changed to 3
1569242004554|INFO|Script1@558:invoke|Created static node 3 (3) @ [0, 0, 0]
1569242004554|INFO|org.arl.unet.nodeinfo.NodeInfo@558:setAddress|Node address changed to 4
1569242004554|INFO|Script1@558:invoke|Created static node 4 (4) @ [0, 0, 0]
1569242004555|INFO|Script1@558:invoke| --- BEGIN SIMULATION #1 ---
0|INFO|org.arl.unet.sim.SimulationContainer@558:init|Initializing agents...
0|INFO|org.arl.unet.sim.SimulationAgent/1@561:invoke|Loading simulator : SimulationAgent
0|INFO|org.arl.unet.nodeinfo.NodeInfo/1@560:init|Loading agent node v3.0
0|INFO|org.arl.unet.sim.HalfDuplexModem/1@559:init|Loading agent phy v3.0
  :
  :
5673|INFO|org.arl.unet.sim.SimulationAgent/4@570:call|TxFrameNtf:INFORM[type:DATA txTime:2066947222]
6511|INFO|org.arl.unet.sim.SimulationAgent/3@567:call|TxFrameNtf:INFORM[type:DATA txTime:1157370743]
10919|INFO|org.arl.unet.sim.SimulationAgent/4@570:call|TxFrameNtf:INFORM[type:DATA txTime:2072193222
```

Note that the timestamp (first column) changes from the clock time to discrete event time when the simulation starts, and switches back to clock time when the simulation ends.

30.3. Trace file

A trace file contains information about all packet creation, transmission, reception and drop events. It also contains details of node motion.

The default, the trace file format is similar to the NS2 NAM trace, and the trace filename is `logs/trace.nam`. The tracer also computes basic statistics including queued packet count, transmitted packet count, received packet count, dropped packet count, offered load, actual load, average packet latency and normalized throughput. An extract from the trace file is shown below:

```
# BEGIN SIMULATION 1
n -t 8.005000 -s 3 -x 0.000000 -y 0.000000 -Z 0.000000 -a 3
+ -t 8.005000 -s 3 -d 2 -i 40839989 -p 0 -x {3.0 2.0 -1 ------- null}
- -t 8.005000 -s 3 -d 2 -i 40839989 -p 0 -x {3.0 2.0 -1 ------- null}
n -t 8.005000 -s 1 -x 0.000000 -y 0.000000 -Z 0.000000 -a 1
n -t 8.005000 -s 2 -x 0.000000 -y 0.000000 -Z 0.000000 -a 2
n -t 8.005000 -s 4 -x 0.000000 -y 0.000000 -Z 0.000000 -a 4
r -t 9.005000 -s 3 -d 2 -i 40839989 -p 0 -x {3.0 2.0 -1 ------- null}
r -t 9.005000 -s 3 -d 1 -i 40839989 -p 0 -x {3.0 2.0 -1 ------- null}
r -t 9.005000 -s 3 -d 4 -i 40839989 -p 0 -x {3.0 2.0 -1 ------- null}
+ -t 42.042000 -s 1 -d 2 -i 254433913 -p 0 -x {1.0 2.0 -1 ------- null}
- -t 42.042000 -s 1 -d 2 -i 254433913 -p 0 -x {1.0 2.0 -1 ------- null}
r -t 43.042000 -s 1 -d 2 -i 254433913 -p 0 -x {1.0 2.0 -1 ------- null}
r -t 43.042000 -s 1 -d 4 -i 254433913 -p 0 -x {1.0 2.0 -1 ------- null}
r -t 43.042000 -s 1 -d 3 -i 254433913 -p 0 -x {1.0 2.0 -1 ------- null}
  :
  :
d -t 584.925000 -s 1 -d 4 -i 259068939 -p 0 -x {1.0 4.0 -1 ------- null} -y CLEAR
+ -t 584.925000 -s 4 -d 1 -i -2069119004 -p 0 -x {4.0 1.0 -1 ------- null}
- -t 584.925000 -s 4 -d 1 -i -2069119004 -p 0 -x {4.0 1.0 -1 ------- null}
d -t 584.925000 -s 4 -d 1 -i -2069119004 -p 0 -x {4.0 1.0 -1 ------- null} -y COLLISION
d -t 584.925000 -s 4 -d 2 -i -2069119004 -p 0 -x {4.0 1.0 -1 ------- null} -y COLLISION
d -t 584.925000 -s 4 -d 3 -i -2069119004 -p 0 -x {4.0 1.0 -1 ------- null} -y COLLISION
d -t 585.747000 -s 1 -d 2 -i 259068939 -p 0 -x {1.0 4.0 -1 ------- null} -y BAD_FRAME
d -t 585.747000 -s 1 -d 3 -i 259068939 -p 0 -x {1.0 4.0 -1 ------- null} -y BAD_FRAME
  :
  :
# STATS: q=621, t=621, r=506, d=115, O=0.099, L=0.099, D=0.000, T=0.080
# END SIMULATION 1
```

Lines starting with `n` log node locations/motion. Lines starting with `+` denote packet arrival into the transmit queue. Lines starting with `-` log packet removal from the transmit queue, i.e., transmission. Lines starting with `r` denote packet reception (or overhearing). Lines starting with `d` log packet drops, and specify a reason for the drop. `CLEAR` indicates a packet transmission/reception abort due to a `ClearReq` request. `COLLISION` indicates that the packet was dropped because the node was busy receiving or transmitting another packet. `BAD_FRAME` indicates that the packet was corrupted (possibly due to interference from a colliding packet).

For more details on the trace file format, see NS2 NAM trace format.

While the trace provides a simple file format and collects statistics for you, the events monitored by the trace are currently limited to PHYSICAL service events. If you need to monitor or log events from other agents, you would want to use log files.

Customizing your trace file

The trace can be configured in the simulation script. By default, the trace uses the `NamTracer` class to create a `logs/trace.nam` file:

```
trace = new NamTracer()
trace.open('logs/trace.nam')
```

An alternate class extending the `Tracer` abstract class can be specified, if you wish to write your own advanced custom tracer.

Chapter 31. Modems and channel models

In Chapter 29 and Chapter 30, we learned how to simulate Unets with many nodes, using a single computer. In fact, we have been using simulations throughout the handbook. In a simulated Unet, most agents are identical to the agents running in nodes on a real Unet. However, since the communication in a simulated Unet does not use a modem in water, we need a model for how a real modem behaves.

31.1. Modem models

A modem usually provides the PHYSICAL service (and optionally, the BASEBAND service). In a simulation, we need a simulated modem to provide these services with behaviors as close to reality as possible. The agent that models the modem behavior is called a *modem model*. The Unet simulator comes with the `HalfDuplexModem` model that can be customized to emulate various underwater acoustic modems.

Since the `HalfDuplexModem` is the default modem model, we don't need to explicitly specify it. But if we wanted to, we could do it in the simulation script:

```
modem = [ model: org.arl.unet.sim.HalfDuplexModem ]
```

Some modem manufacturers may provide you with a modem model that more accurately matches the behaviors of their modem. This can be useful when simulating networks with modems from specific vendors.

We can specify properties that control the behavior of the modem. You can either specify them while declaring the modem:

```
modem = [
  model:            org.arl.unet.sim.HalfDuplexModem,
  dataRate:         [800.bps, 2400.bps],
  frameLength:      [16.bytes, 64.bytes],
  powerLevel:       [0.dB, -10.dB],
  preambleDuration: 5.ms
]
```

or later, by assigning the properties individually:

```
modem.dataRate = [800.bps, 2400.bps]
modem.frameLength = [16.bytes, 64.bytes]
modem.powerLevel = [0.dB, -10.dB]
modem.preambleDuration = 5.ms
```

Indexed properties `dataRate`, `frameLength`, `maxFrameLength`, `janus` and `powerLevel` are specified as 3-tuples, with the first entry corresponding to the CONTROL channel, the second for the DATA channel, and the third for the JANUS frame type. If JANUS support is not required, the properties may be specified as 2-tuples.

If you run a realtime simulation with `modem.dataRate = [800.bps, 2400.bps]`, connect to a node's shell, and then type in `phy[CONTROL].dataRate`, you may be surpirsed to see a much lower data rate (436 bps in this example). The 800 bps is the signaling rate, and exludes overheads from preamble and headers. The 436 bps is the effective average data rate across the frame, and includes all overheads.

Short descriptions and default values of these properties are shown below:

`modem.dataRate = [256, 1024, 80]`
: Communication link data rate (bps).

`modem.frameLength = [24, 64, 8]`
: Default frame length (bytes).

`modem.maxFrameLength = [128, 512, 128]`
: Maximum frame length (bytes)

`modem.janus = [false, false, true]`
: Support for JANUS frames.

`modem.powerLevel = [-10, -10, -10]`
: Transmit power level (dB re `refPowerLevel`).

In addition to the above indexed properties, several other properties control the modem behavior:

`modem.signalPowerLevel = -10`
: Transmit power level (dB re `refPowerLevel`) for baseband signals.

`modem.preambleDuration = 0.2`
: Frame detection preamble duration (s).

`modem.headerLength = 8`
: Frame header length (bytes).

`modem.timestampLength = 6`
: Timestamp length (bytes), for timestamped frames.

`modem.txDelay = 0.05`
: Transmission delay when switching from receive to transmit mode (s).

`modem.timestampedTxDelay = 1.0`
: Transmission delay when scheduling transmission of a timestamped packet (s).

`modem.maxPowerLevel = 0`
: Maximum allowable transmit power level (dB re `refPowerLevel`).

`modem.minPowerLevel = -96`
: Minimum allowable transmit power level (dB re `refPowerLevel`).

`modem.refPowerLevel = 185`
: Reference transmit power level (dB re µPa @ 1m).

`modem.rxSensitivity = -200`
: Reference receive sensitivity (dB re µPa).

`modem.carrierFrequency = 12000`
: Carrier frequency (Hz).

`modem.basebandRate = 12000`
: Baseband sampling rate (samples/second).

`modem.basebandRxDuration = 1.0`
: Baseband reception duration (s).

`modem.maxSignalLength = 65536`
: Maximum allowable baseband signal length.

A modem model simulates the half-duplex nature of the modem, propagation delay, interference, packet detection and packet loss. In order to do this accurately, it uses a channel model.

31.2. Channel models

Channel models implement the `ChannelModel` interface. The default channel model is the `BasicAcousticChannel`, but can be reconfigured in the simulation script. Again, channel models can use either syntax:

```
channel = [
  model:              org.arl.unet.sim.channels.ProtocolChannelModel,
  communicationRange: 3000.m,
  pDetection:         0.9,
  pDecoding:          0.8
]
```

or

```
channel.model = org.arl.unet.sim.channels.ProtocolChannelModel
channel.communicationRange = 1000.m
channel.pDetection = 0.9
channel.pDecoding = 0.8
```

The properties supported by a channel model depend on the specifics of that model. Let us next look at a few channel models that come with the Unet simulator.

31.2.1. Protocol channel model

The protocol channel model (`ProtocolChannelModel`) is the simplest of the channel models available in the Unet simulator. Although simple, it captures important first-order effects such as propagation delay, limited communication range, interference range, and collisions. It also captures the probabilistic nature of the channel. It therefore serves as a good first order approximation that is also amenable to mathematical analysis.

The protocol channel model is parametrized by a sound speed `c`, communication range `Rc`, detection

range Rd, an interference range Ri, probability of detection pd, and a probability of decoding pc. Successful communication is possible at a range $R \leq Rc$ with a probability $pd \times pc$. At a range $Rc < R \leq Rd$, a frame may be detected with probability pd, but not successfully decoded. At any range $R \leq Ri$, a frame interferes with another frame that is being received at the same time, and causes a collision. Both frames are lost (not successfully decoded) during a collision. At a range $R > Ri$, a frame is not detected and does not interfere with other frames.

To select the protocol model, the simulation script must explicitly set it as the channel.model. The parameters of the model can be configured in the simulation script. The configuration of the channel with default parameter values is shown below:

```
import org.arl.unet.sim.channels.*

channel.model = org.arl.unet.sim.channels.ProtocolChannelModel

channel.soundSpeed = 1500.mps           // c
channel.communicationRange = 2000.m     // Rc
channel.detectionRange = 2500.m         // Rd
channel.interferenceRange = 3000.m      // Ri
channel.pDetection = 1                  // pd
channel.pDecoding = 1                   // pc
```

31.2.2. Basic acoustic channel model

The basic acoustic channel model (BasicAcousticChannel) is the default channel model in the simulator. It provides a good balance between accuracy, applicability and simulation speed. The model is composed of two parts: an acoustic model (UrickAcousticModel) based on average transmission loss, and a communication model (BPSKFadingModel) based on high time-bandwidth product detection preamble and binary phase shift keying (BPSK) communication in a Rician or Rayleigh fading channel.

Urick acoustic model

The acoustic model is parametrized by carrier frequency f, bandwidth B, spreading loss factor α, water temperature T°C, salinity S ppt, noise power spectral density level N0 dB re µPa/√Hz and water depth d. The default values are shown below:

```
import org.arl.unet.sim.channels.*

channel.model = BasicAcousticChannel

channel.carrierFrequency = 25.kHz       // f
channel.bandwidth = 4096.Hz             // B
channel.spreading = 2                   // α
channel.temperature = 25.C              // T
channel.salinity = 35.ppt               // S
channel.noiseLevel = 60.dB              // N0
channel.waterDepth = 20.m               // d
```

The acoustic model automatically computes the sound speed c [Mackenzie, JASA, 1981], transmission loss TL [Urick 3rd ed, p105-111] and total noise level NL. The total signal-to-noise ratio is then given by SNR = SL - TL - NL, where SL is the source level of the transmission in dB re µPa @ 1m.

BPSK fading model

The fading communication model uses the above SNR to simulate detection and successful decoding. The model is parametrized by the Rician fading parameter K, fast/slow fading, acceptable probability pfa of false alarm during detection, and a processing gain G. The default values are shown below:

```
channel.ricianK = 10                    // K
channel.fastFading = true               // fast/slow fading
channel.pfa = 1e-6                      // pfa
channel.processingGain = 0.dB           // G
```

For a detection preamble of duration t seconds and bandwidth B, we have an effective SNR' = SNR + 10 log(Bt) after pulse compression. We assume Rician fading (or Rayleigh fading if K = 0) and Gaussian noise such that the average SNR is SNR' to simulate detection.

For the BPSK communication signal with data rate D bits/second, we compute Eb/N0 = SNR + 10 log(B/D) + G. We then simulate bit errors assuiming Rician fading (or Rayleigh fading if K = 0) and Gaussian noise. If fast fading is enabled, each bit generates an independent realization for the Rician fading variate. If fast fading is disabled, the entire frame uses a single realization of the Rician fading variate. If all bits are successful, the frame is successfully decoded. If any bit is in error, the frame is deemed to have failed at decoding.

31.2.3. MISSION 2012 and 2013 channel models

Although channel modeling can provide useful approximations to an underwater channel, there is no real substitute to experimenting at sea. The MISSION 2012 and MISSION 2013 experiments were conducted over several weeks in October 2012 and November 2013 in Singapore waters. Extensive channel measurements were made between Unet nodes deployed during the experiment. These measurements allow us to estimate packet detection probabilities and packet error probabilities on various network links. Although these probabilities are generally time-varying, we can estimate instantaneous probabilities from measurements over a short interval during which the environmental conditions are relatively stable. These can be used to generate a protocol channel model that accurately models the channel between the nodes during the experiment. Any protocol simulations using this model then accurately predict what would have happened if the protocol was tested at sea during the experiment. This may be a great way to benchmark protocols in realistic deployment conditions.

To use the Mission2012a model for simulation, set the appropriate channel model and node addresses/locations in the simulation script:

```
import org.arl.unet.sim.channels.*

channel.model = Mission2012a

simulate {
  Mission2012a.nodes.each { addr ->
    node "P$addr", address: addr, location: Mission2012a.nodeLocation[addr]
  }
}
```

The Mission2013a and Mission2013b models are used in a similar way.

We have already been using the `Mission2013a` channel model when using the `samples/mission2013-network.groovy` simulation in Section 6.1. You may wish to take a look at the simulation script now, to understand how it works.

31.2.4. Developing custom channel models

While the above channel models meet the simulation needs for many applications, custom channel models may be developed to meet special research needs. Although developing and testing a model from scratch can be a daunting task, the `ProtocolChannelModel` and the `AbstractAcousticChannel` classes provide excellent starting points to customize the channel models. In this section, we see how each of the classes can be used to create custom channels.

Extending the ProtocolChannelModel

The `ProtocolChannelModel` can be customized to provide per-link detection and decoding probabilities. The `Mission2012a` and `Mission2013a` models do exactly this. To illustrate how this is done, let us take a look at the following code sample:

```
import org.arl.unet.sim.*
import org.arl.unet.sim.channels.ProtocolChannelModel

class Mission2012Channel extends ProtocolChannelModel {

  static final def nodes = [21, 22, 27, 28, 29]
  static final def nodeLocation = [
    21: [   0,    0,  -5],
    22: [ 398, -105, -18],
    27: [-434, -499, -12],
    28: [ -32,  279, -20],
    29: [-199, -307, -12]
  ]
  static def pNoDetect = [
    [    0, 0.047, 0.095, 0.026, 0.056],
    [0.032,     0, 0.228, 0.139, 0.081],
    [0.047, 0.174,     0, 0.025, 0.011],
    [0.019, 0.060, 0.040,     0, 0.420],
    [0.026, 0.018, 0.009, 0.048,     0]
  ]
  static def pNoDetectOrDecode = [
    [    0, 0.157, 0.643, 0.197, 0.239],
    [0.184,     0, 0.870, 0.639, 0.435],
    [0.326, 0.826,     0, 0.975, 0.023],
    [0.038, 0.160, 0.760,     0, 0.900],
    [0.070, 0.070, 0.018, 0.871,     0]
  ]

  float getProbabilityDetection(Reception rx) {
    int from = nodes.indexOf(rx.from)
    int to = nodes.indexOf(rx.address)
    if (from < 0 || to < 0) return 0
    return 1-pNoDetect[from][to]
  }

  float getProbabilityDecoding(Reception rx) {
    int from = nodes.indexOf(rx.from)
    int to = nodes.indexOf(rx.address)
    if (from < 0 || to < 0) return 0
    return (1-pNoDetectOrDecode[from][to])/(1-pNoDetect[from][to])
  }

}
```

The nodes during the MISSION 2012 experiment have addresses 21, 22, 27, 28 and 29. The node locations and inter-node detection/decoding probabilities are measured and tabulated in the model. The model uses these measurements to simulate packet loss.

Extending the AbstractAcousticChannel

The `AbstractAcousticChannel` class provides a framework for acoustic simulation channels, including functionality for collision detection. The `BasicAcousticChannel` class extends the `AbstractAcousticChannel` class and provides implementation for an acoustic model (`UrickAcousticModel`) and a communication model (`BPSKFadingModel`):

```
class BasicAcousticChannel extends AbstractAcousticChannel {
  @Delegate UrickAcousticModel acoustics = new UrickAcousticModel(this)
  @Delegate BPSKFadingModel comms = new BPSKFadingModel(this)
}
```

To customize an acoustic channel model, one may extend or replace the acoustic or communication models. For example, if we wish to have a deep sea noise model where the noise power was a function of a new parameter `seaState`, we could extend the `UrickAcousticModel`:

```
import org.arl.unet.sim.channels.UrickAcousticModel

class MyAcousticModel extends UrickAcousticModel {

  // map of sea state to noise power (dB re uPa^2/Hz)
  private final def noiseLevel = [ 0: 20, 1: 30, 2: 35, 3: 40, 4: 42, 5: 44, 6: 46 ]

  // sea state parameter
  float seaState = 2

  double getNoisePower() {
    return Math.pow(10, noiseLevel[seaState]/10) * model.bandwidth
  }

}
```

and then replace the `BasicAcousticChannel` model with out own version:

```
import org.arl.unet.sim.channels.*

class MyAcousticChannel extends AbstractAcousticChannel {
  @Delegate UrickAcousticModel acoustics = new MyAcousticModel(this)
  @Delegate BPSKFadingModel comms = new BPSKFadingModel(this)
}
```

Similarly, the communication model can be extended or replaced too.

Appendices

Appendix A: MySimpleHandshakeMac

MySimpleHandshakeMac.groovy from Section 28.4:

```
import org.arl.fjage.*
import org.arl.unet.*
import org.arl.unet.phy.*
import org.arl.unet.mac.*
import org.arl.unet.nodeinfo.*

class MySimpleHandshakeMac extends UnetAgent {

  ////// protocol constants

  private final static int PROTOCOL = Protocol.MAC

  private final static float  RTS_BACKOFF     = 2.seconds
  private final static float  CTS_TIMEOUT     = 5.seconds
  private final static float  BACKOFF_RANDOM  = 5.seconds
  private final static float  MAX_PROP_DELAY  = 2.seconds
  private final static int    MAX_RETRY       = 3
  private final static int    MAX_QUEUE_LEN   = 16

  ////// reservation request queue

  private Queue<ReservationReq> queue = new ArrayDeque<ReservationReq>(MAX_QUEUE_LEN)

  ////// PDU encoder/decoder

  private final static int RTS_PDU = 0x01
  private final static int CTS_PDU = 0x02

  private final static PDU pdu = PDU.withFormat {
    uint8('type')         // RTS_PDU/CTS_PDU
    uint16('duration')    // ms
  }

  ////// protocol FSM

  private enum State {
    IDLE, RTS, TX, RX, BACKOFF
  }

  private enum Event {
    RX_RTS, RX_CTS, SNOOP_RTS, SNOOP_CTS
  }

  private FSMBehavior fsm = FSMBuilder.build {

    int retryCount = 0
    float backoff = 0
    def rxInfo

    state(State.IDLE) {
      action {
        if (!queue.isEmpty()) {
          after(rnd(0, BACKOFF_RANDOM)) {
            setNextState(State.RTS)
          }
        }
```

```
      block()
    }
    onEvent(Event.RX_RTS) { info ->
      rxInfo = info
      setNextState(State.RX)
    }
    onEvent(Event.SNOOP_RTS) {
      backoff = RTS_BACKOFF
      setNextState(State.BACKOFF)
    }
    onEvent(Event.SNOOP_CTS) { info ->
      backoff = info.duration + 2*MAX_PROP_DELAY
      setNextState(State.BACKOFF)
    }
  }

  state(State.RTS) {
    onEnter {
      Message msg = queue.peek()
      def bytes = pdu.encode(
        type: RTS_PDU,
        duration: Math.ceil(msg.duration*1000))
      phy << new TxFrameReq(
        to: msg.to,
        type: Physical.CONTROL,
        protocol: PROTOCOL,
        data: bytes)
      after(CTS_TIMEOUT) {
        if (++retryCount >= MAX_RETRY) {
          sendReservationStatusNtf(queue.poll(), ReservationStatus.FAILURE)
          retryCount = 0
        }
        setNextState(State.IDLE)
      }
    }
    onEvent(Event.RX_CTS) {
      setNextState(State.TX)
    }
  }

  state(State.TX) {
    onEnter {
      ReservationReq msg = queue.poll()
      retryCount = 0
      sendReservationStatusNtf(msg, ReservationStatus.START)
      after(msg.duration) {
        sendReservationStatusNtf(msg, ReservationStatus.END)
        setNextState(State.IDLE)
      }
    }
  }

  state(State.RX) {
    onEnter {
      def bytes = pdu.encode(
        type: CTS_PDU,
        duration: Math.round(rxInfo.duration*1000))
      phy << new TxFrameReq(
        to: rxInfo.from,
        type: Physical.CONTROL,
        protocol: PROTOCOL,
        data: bytes)
      after(rxInfo.duration + 2*MAX_PROP_DELAY) {
```

```
          setNextState(State.IDLE)
        }
        rxInfo = null
      }
    }

    state(State.BACKOFF) {
      onEnter {
        after(backoff) {
          setNextState(State.IDLE)
        }
      }
      onEvent(Event.SNOOP_RTS) {
        backoff = RTS_BACKOFF
        reenterState()
      }
      onEvent(Event.SNOOP_CTS) { info ->
        backoff = info.duration + 2*MAX_PROP_DELAY
        reenterState()
      }
    }

  } // of FSMBuilder

  ////// agent startup sequence

  private AgentID phy
  private int addr

  @Override
  void setup() {
    register Services.MAC
  }

  @Override
  void startup() {
    phy = agentForService Services.PHYSICAL
    subscribe(phy)
    subscribe(topic(phy, Physical.SNOOP))
    add new OneShotBehavior({
      def nodeInfo = agentForService Services.NODE_INFO
      addr = get(nodeInfo, NodeInfoParam.address)
    })
    add(fsm)
  }

  ////// process MAC service requests

  @Override
  Message processRequest(Message msg) {
    switch (msg) {
      case ReservationReq:
        if (msg.to == Address.BROADCAST || msg.to == addr)
          return new RefuseRsp(msg, 'Reservation must have a destination node')
        if (msg.duration <= 0 || msg.duration > maxReservationDuration)
          return new RefuseRsp(msg, 'Bad reservation duration')
        if (queue.size() >= MAX_QUEUE_LEN)
          return new Message(msg, Performative.FAILURE)
        queue.add(msg)
        fsm.restart()    // tell fsm to check queue, as it may block if empty
        return new ReservationRsp(msg)
      case ReservationCancelReq:
      case ReservationAcceptReq:
```

```
      case TxAckReq:
        return new RefuseRsp(msg, 'Not supported')
    }
    return null
  }

  ////// handle incoming MAC packets

  @Override
  void processMessage(Message msg) {
    if (msg instanceof RxFrameNtf && msg.protocol == PROTOCOL) {
      def rx = pdu.decode(msg.data)
      def info = [from: msg.from, to: msg.to, duration: rx.duration/1000.0]
      if (rx.type == RTS_PDU)
        fsm.trigger(info.to == addr ? Event.RX_RTS : Event.SNOOP_RTS, info)
      else if (rx.type == CTS_PDU)
        fsm.trigger(info.to == addr ? Event.RX_CTS : Event.SNOOP_CTS, info)
    }
  }

  ////// expose parameters that are expected of a MAC service

  final int reservationPayloadSize = 0            // read-only parameters
  final int ackPayloadSize = 0
  final float maxReservationDuration = 65.535

  @Override
  List<Parameter> getParameterList() {            // publish list of all exposed parameters
    return allOf(MacParam)
  }

  boolean getChannelBusy() {                      // considered busy if fsm is not IDLE
    return fsm.currentState.name != State.IDLE
  }

  float getRecommendedReservationDuration() {     // recommended duration: one DATA packet
    return get(phy, Physical.DATA, PhysicalChannelParam.frameDuration)
  }

  ////// utility methods

  private void sendReservationStatusNtf(ReservationReq msg, ReservationStatus status) {
    send new ReservationStatusNtf(
      recipient: msg.sender,
      inReplyTo: msg.msgID,
      to: msg.to,
      from: addr,
      status: status)
  }

}
```