Practical Contiki-NG

Programming for Wireless Sensor Networks

Agus Kurniawan

Apress®

Practical Contiki-NG

Programming for Wireless Sensor Networks

Agus Kurniawan

Apress®

Practical Contiki-NG: Programming for Wireless Sensor Networks

Agus Kurniawan
Depok, Jawa Barat, Indonesia

ISBN-13 (pbk): 978-1-4842-3407-5 ISBN-13 (electronic): 978-1-4842-3408-2
https://doi.org/10.1007/978-1-4842-3408-2

Library of Congress Control Number: 2018947346

Managing Director, Apress Media LLC: Welmoed Spahr
Acquisitions Editor: Natalie Pao
Development Editor: James Markham
Coordinating Editor: Jessica Vakili

Cover designed by eStudioCalamar

Cover image designed by Freepik (www.freepik.com)

Distributed to the book trade worldwide by Springer Science+Business Media New York, 233 Spring Street, 6th Floor, New York, NY 10013. Phone 1-800-SPRINGER, fax (201) 348-4505, email orders-ny@springer-sbm.com, or visit www.springeronline.com. Apress Media, LLC is a California LLC and the sole member (owner) is Springer Science + Business Media Finance Inc (SSBM Finance Inc). SSBM Finance Inc is a **Delaware** corporation.

For information on translations, please email rights@apress.com, or visit http://www.apress.com/rights-permissions.

Apress titles may be purchased in bulk for academic, corporate, or promotional use. eBook versions and licenses are also available for most titles. For more information, reference our Print and eBook Bulk Sales web page at http://www.apress.com/bulk-sales.

Any source code or other supplementary material referenced by the author in this book is available to readers on GitHub via the book's product page, located at www.apress.com/978-1-4842-3407-5. For more detailed information, please visit http://www.apress.com/source-code.

Printed on acid-free paper

Table of Contents

About the Author

Agus Kurniawan is a lecturer, researcher, IT consultant, and author. He has 17 years of experience in various software and hardware development projects, delivering materials in training and workshops, and technical writing. He has been awarded the Microsoft Most Valuable Professional (MVP) award 14 years in a row.

His topic interests are software engineering, embedded systems, networking, and security systems. He has been working as a lecturer and researcher at the Faculty of Computer Science, Universitas Indonesia. Currently, he is pursuing a PhD in computer science at the Freie Universität in Berlin, Germany. He can be reached on his blog at `http://blog.aguskurniawan.net` and Twitter at `@agusk2010`.

About the Technical Reviewer

Chaim Krause is first and foremost a #geek. Other hashtags used to define him are (in no particular order) #autodidact, #maker, #gamer, #raver, #teacher, #adhd, #edm, #wargamer, #privacy, #liberty, #civilrights, #computers, #developer, #software, #dogs, #cats, #opensource, #technicaleditor, #author, #polymath, #polyglot, #american, #unity3d, #javascript, #smartwatch, #linux, #energydrinks, #midwesterner, #webmaster, #robots, #sciencefiction, #sciencefact, #universityofchicago, #politicalscience, and #bipolar. He can always be contacted at `chaim@chaim.com` and goes by the Nom de Net Tinjaw.

Acknowledgments

I would like to thank Apress for all their help in making this book possible. Specifically, I would like to thank Natalie Pao and Jessica Vakili, my coordinating editors, for helping me to stay focused and to overcome many obstacles. Without them, this book would not have been possible.

Special thanks to James Markham, my development editor, and Chaim Krause, technical reviewer, Nirmal Selvaraj, Production Editor, C. Dulcy Nirmala, Senior Executive Project Manager for all his suggestions during the editorial review process to help make this a great book.

I would also like to thank the Contiki and Contiki-NG communities anywhere in the world for contributing and making learning and developing Contiki-NG easy.

Last, but not least, a thank you to my wife, Ela, and my children, Thariq and Zahra, for their great support while I completed this book.

Introduction

Wireless Sensor Networks (WSN) are one of the research and technology topics for which researchers, developers, and makers develop applications with specific purposes. Contiki-NG is one of the WSN platforms used to build WSN programs supported by various hardware platforms. This book is designed for developers and researchers who want to build Contiki-NG programs for general and specific purposes.

For the Readers

This book assumes you have some programming experience. It is also written for someone who has developed programs using C/C++ and wants to develop a Wireless Sensor Network (WSN) application with the Contiki-NG platform.

How This Book Is Organized

This book is designed with a step-by-step approach. You will learn how to develop a WSN with the Contiki-NG platform. You will also explore some Contiki-NG libraries and APIs to implement certain scenarios.

You will learn how to develop a Contiki-NG program. This book explains how Contiki-NG performs sensing and actuating. You will also see how to communicate with other Contiki-NG platforms and external systems, such as cloud servers.

Required Software, Materials, and Equipment

In general, you need a computer with Linux, Windows, or Mac OS installed. Linux is recommended. You should install all toolchains and Contiki-NG project codes on your computer.

We need Contiki-NG mote hardware to implement our demo. This book uses Telosb/sky and TI LaunchPad CC2650 boards for testing.

CHAPTER 1

Introduction to Wireless Sensor Networks

Wireless Sensor Networks (WSN) are a research and technology topic for which researchers, developers, and makers develop applications for specific purposes. In this chapter, we will learn and explore what a WSN is and try to develop one using the WSN platform Contiki and its update, Contiki-NG.

The following is a list of topics we will cover in this chapter:

- Introduce Wireless Sensor Networks.
- Introduce Contiki OS.
- Explore WSN hardware and platform.
- Introduce Contiki-NG project.
- Set up Contiki-NG development environment.
- Build a simple Contiki application.
- Work with Contiki simulator.
- Debug Contiki application.

A. Kurniawan, *Practical Contiki-NG*, https://doi.org/10.1007/978-1-4842-3408-2_1

Introduction to Wireless Sensor Networks

A Wireless Sensor Network (WSN) is a board system with the connectivity capability to sense data and/or to perform actions. Sometimes the WSN board is called a WSN mote. The main objective of implementing a WSN mote is to capture physical objects in digital form and then transfer them to a certain server. Research on WSN topics is an intense study area since there are a lot of problems in need of solving, such as mote hardware design, networking, infrastructure, and security.

Nowadays, hardware manufacturers grow up fast. You will find that there are a lot of new boards on the market, such as Arduino, Raspberry Pi, BeagleBone, Intel Edison, NodeMCU, Teensy, Tessel, and so on. This is the era of the Internet of Things (IoT). It's estimated that there are billions of IoT devices connected to the Internet, based on Gatner's report. Since IoT board demand is high, the board price could be quite cheap. Furthermore, the open source hardware movement has had an impact on the growing board industry. People can design and make their own boards for special purposes.

Back to our WSN mote topic—how to describe a WSN mote? In general, a WSN mote consists of a microcontroller (MCU), sensor/actuator, and wireless module. You can see it in Figure 1-1. The MCU is the center of processing in a WSN mote. It has a responsibility to ensure the system runs well. In other designs, the MCU can be replaced by an MPU (microprocessor), depending on whether there is a battery issue or not. The second part is the sensor/actuator. A sensor can capture physical objects, such as temperature, humidity, and compass direction. An actuator can perform a certain action, such as lighting an LED, generating sound, or running a motor. Some WSN motes may provide sensor devices only, but other WSN motes may use both a sensor and an actuator inside the board. Again, it depends on your design. The last part is the wireless module. It's used to transfer data from the mote to a network device; for instance, gateway, server application, or cloud application. Selecting the wireless module type will have an impact on what protocol will be used to communicate with other motes and servers. Most WSN motes use IEEE 802.15.4 as their network protocol.

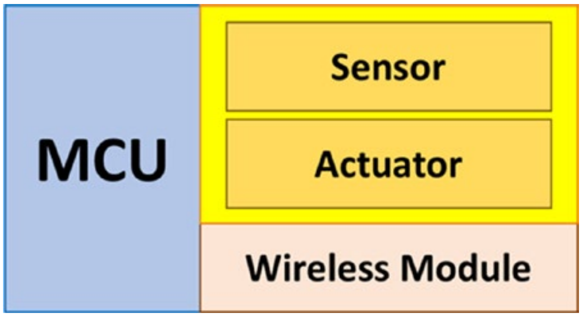


Figure 1-1. *General model of Wireless Sensor Network (WSN) mote*

Sometimes makers will build WSN devices in several forms based on their roles. A WSN mote may only consist of an MCU and a radio module, without sensor and actuator devices. Some WSN motes will provide an MCU, sensor/actuator devices, and a radio module.

How can the WSN mote reach the server? This is a common issue in WSN implementation. If a WSN mote has the same protocol as the servers on the network module, it can communicate with the server directly. This method may take more battery usage in the mote since most servers use advanced protocol without battery issues. Alternatively, we can use a gateway, which is used as a bridge between WSN motes and servers. Some gateways have the capability to translate the WSN mote's protocol to the target server's protocol so they can exchange data. The gateway can be implemented to monitor the existing WSN motes. You can see how WSN motes communicate with another system through a gateway in Figure 1-2.

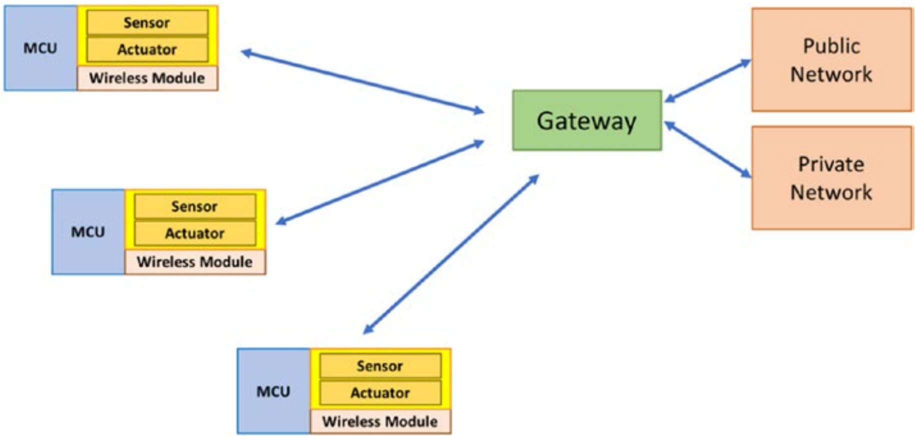


Figure 1-2. *A connectivity model for several WSN motes*

Introduction to Contiki OS

Contiki is a WSN platform that provides software and hardware. Contiki was created by Adam Dunkels in 2002. Now, the Contiki project involves both companies and contributors. This project has released open source software and hardware. The operating system (OS) in Contiki uses Protothread, which combines multithreading and event-driven programming. On the hardware side, the Contiki project provides hardware schemes so that we can build our own Contiki boards. You can reach the official website for Contiki at `http://www.contiki-os.org`.

The programming model of the Contiki platform implements a preemptive multithreading architecture and an event-driven model. The Contiki programming language uses C syntax for writing programs.

Contiki provides hardware abstractions that encapsulate hardware complexity. This approach makes Contiki work with various hardware, including MCUs and radio modules. General libraries for sensing, actuating, and communication are also provided by Contiki. Users should get more attention on their problems. You can see the general architecture of Contiki in Figure 1-3.

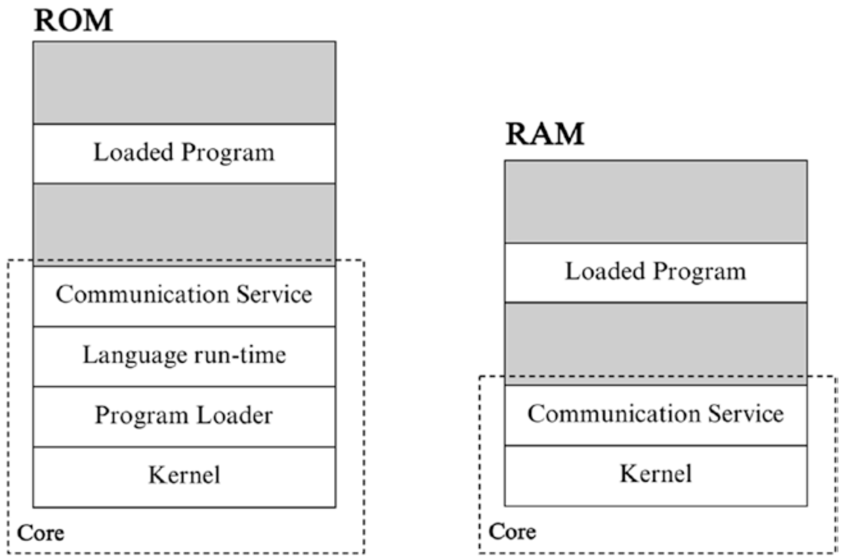


Figure 1-3. *Contiki general architecture*

Kernel, the program loader, the language run-time, and the communication service are static modules within the ROM of Contiki OS. All user programs will be loaded into Loaded Program. Only the kernel and the communication service will be used by the Contiki OS RAM.

Contiki uses a GCC compiler to compile C source code files. We develop Contiki applications written in `*.c` files. After they are compiled, we obtain the binary file. Basically, it converts the application from C program syntax to a native binary file for a specific hardware target. We also can run a C program on the Contiki simulator to verify program behaviors. You can see the flow of programming in Figure 1-4.

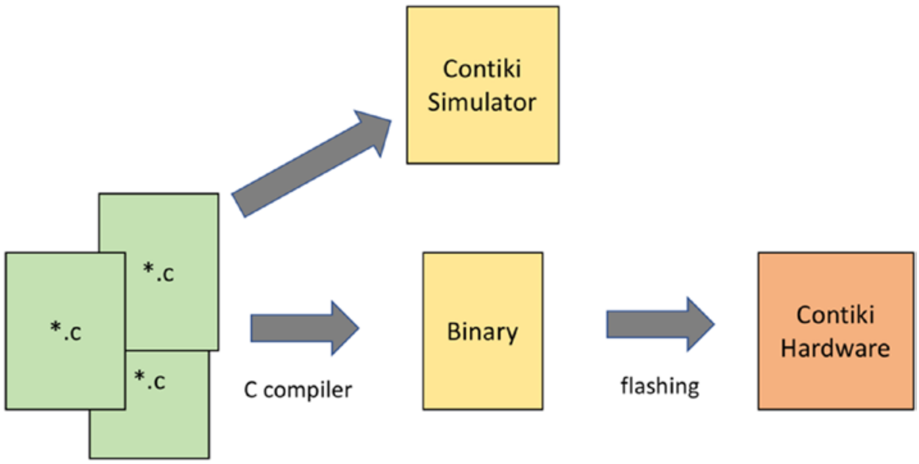


Figure 1-4. *Programming flow for Contiki*

Reviewing WSN Hardware for Contiki

To run Contiki on top of hardware, that hardware needs to fulfill some requirements, especially about the MCU and network module. In this section, we will explore various WSN hardware types that we can use to implement Contiki. A box that consists of a WSN board that has some sensors or actuators is called a WSN mote. If you have a TinyOS mote, you can use that mote to run a Contiki application.

In general, a list of supported Contiki OS can be found on the official website at this link: `http://www.contiki-os.org/hardware.html`. For Contiki-NG, you can see a list of Contiki-NG boards at `https://github.com/contiki-ng/contiki-ng/wiki#the-contiki-ng-platforms`. We will next review some famous WSN mote models that you can use for experimental purposes.

MICAz

MICAz is a mote from Crossbow Technology, MEMSIC. This mote uses an ATmega128L microcontroller and the CC2420 radio chip. ATmega128L is an 8-bit microcontroller from Atmel. This MCU has capabilities such as 128K of in-system, self-programmable flash program memory, 4K of EEPROM, and 4K of internal SRAM. You can explore this MCU by reading its datasheet at `http://www.atmel.com/images/doc2467.pdf`.

On the radio side, this mote uses a CC2420 chip that implements IEEE 802.15.4 protocol. This chip has energy-saving capabilities. You can work in sleep mode on a network layer stack. You can read more information about MICAz at `http://www.memsic.com/wireless-sensor-networks/`. You can see a MICAz board form in Figure 1-5 (source: `http://www.memsic.com/wireless-sensor-networks/`).

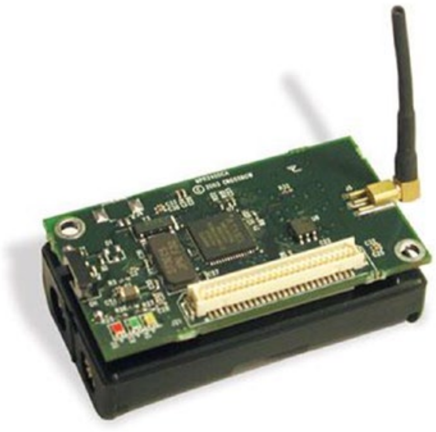


Figure 1-5. *MICAz mote model*

Mica2

Mica2 is similar to the MICAz mote in that the mote uses an Atmel ATmega128L microcontroller; it uses the CC1000 radio chip for the wireless module. The battery connector is also provided to work standalone. You can see the Mica2 mote in Figure 1-6 (source: http://www.snm.ethz.ch/snmwiki/pub/uploads/Projects/mica2.jpg). To develop a program for this mote, you should use a development board to flash the program.

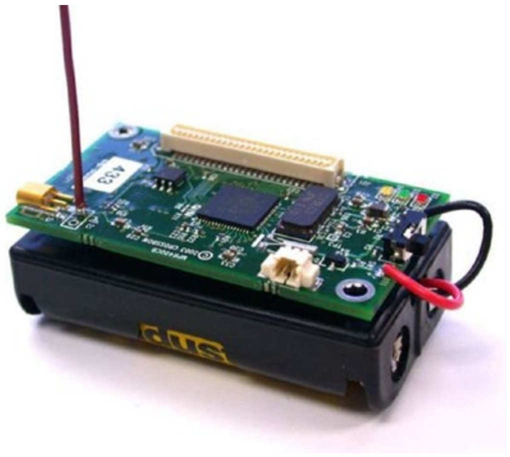


Figure 1-6. *Mica2 mote model*

TelosB

TelosB is the famous model that researchers and makers use for TinyOS implementation. This mote also can be used for the Contiki platform. TelosB motes use an MSP430 microcontroller from Texas Instruments (TI). The MSP340 series in TelosB are built from MSP430x15x, MSP430x16x, and MSP430x161x. Many manufacturers build WSN motes based on the TelosB design. You can see a TelosB mote in Figure 1-7 (source: https://www.advanticsys.com/shop/mtmcm5000msp-p-14.html).

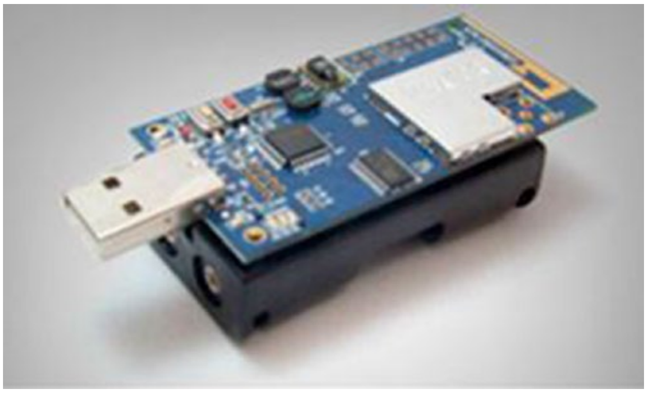


Figure 1-7. *MTM-CM5000-MSP board based on TelosB from Advanticsys*

Iris

Iris is a WSN mote from Crossbow. It's built from an ATmega1281 microcontroller and the Atmel AT86RF230 radio chip. Atmel ATmega1281 has a flash memory that is about 128K and 8K of RAM so you can write programs in more spaces. You can see Iris mote in this site, `http://www.memsic.com/wireless-sensor-networks/`. In Figure 1-8, you can see my Iris mote from Crossbow, which is connected to my notebook.

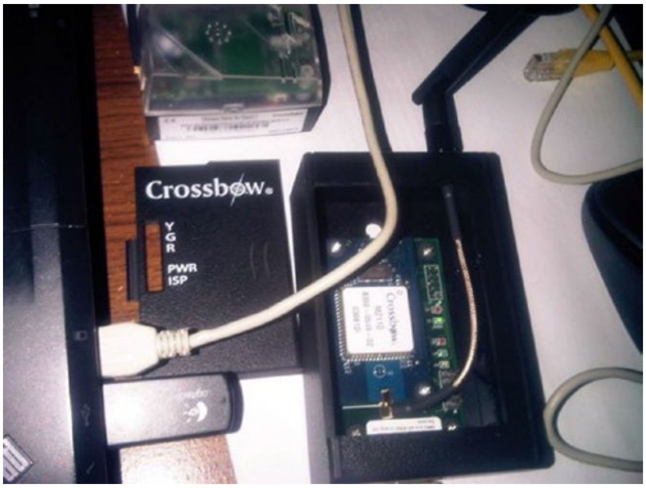


Figure 1-8. *Iris mote from Crossbow*

Custom TinyOS Motes

Independent makers or manufacturers can build their own TinyOS motes, including sensors with specific purposes. The scheme and layout of the TinyOS mote have already been shared so it's not difficult to build your own.

BTnode is a mote based on TinyOS and uses an Atmel ATmega 128K MCU and Chipcon CC1000 radio module. This mote was developed by ETH Zurich. Currently, they have released BTnode revision 3. You can see it in Figure 1-9. Further information about BTnode can be found at `http://www.btnode.ethz.ch/`.

Figure 1-9. *BTnode revision 3 from ETH Zurich*

For more information, you can get a list of compatible TinyOS and Contiki motes at `https://en.wikipedia.org/wiki/List_of_wireless_sensor_nodes`. You can review some WSN motes for your own development.

Z1 Platform

The Z1 platform is a general-purpose development platform for WSN. This board uses an MSP430F2617 low-power microcontroller. The Z1 platform radio modules use a CC2420 transceiver and are IEEE 802.15.4 compliant, which operates at 2.4GHz with an effective data rate of 250Kbps.
For further information, you can visit `https://zolertia.io/`. You can see a form of Z1 platform in Figure 1-10.

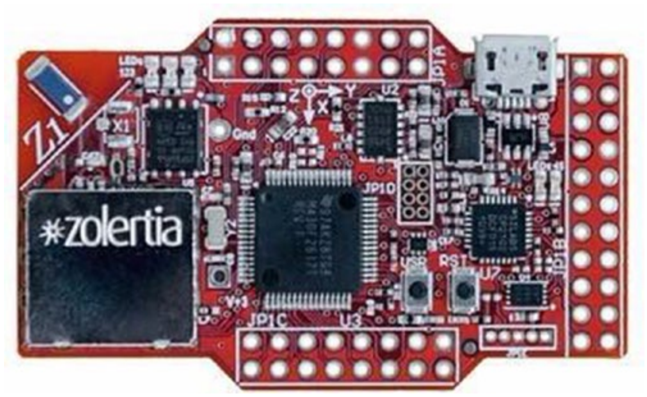


Figure 1-10. *Z1 platform hardware*

Contiki-NG ARM-based Boards

Currently, Contiki-NG offers support for boards with ARM MCU. Based the Contiki-NG document at https://github.com/contiki-ng/contiki-ng/wiki#the-contiki-ng-platforms, we can use several boards with ARM MCU to develop Contiki-NG applications. The following is the list of supported Contiki-NG boards:

- cc2538dk: TI cc2538 development kit
- jn516x: NXP jn516x series
- nrf52dk: Nordic Semiconductor nRF52 development kit
- openmote-cc2538: OpenMote cc2538
- srf06-cc26xx: TI cc26xx and cc13xx platforms
- zoul: Zolertia Zoul platforms: Firefly, RE-mote, and Orion

In this book, I use five board models: Telosb, TI CC2650 LaunchPad, TI CC2650 Sensortag, TI CC1350 LaunchPad, and TI CC1350 Sensortag.

Introducing Contiki-NG

Contiki-NG is a new version of the Contiki project. Contiki-NG provides an RFC-compliant, low-power IPv6 communication stack, enabling Internet connectivity. If you are working with Contiki, I recommend using the latest version—Contiki-NG. This project can be found at `https://github.com/contiki-ng/contiki-ng`.

One advantage of Contiki-NG is that it supports many hardware platforms, including MCU-based ARM. You can bring your favorite boards to build applications for Contiki-NG. This book will cover Contiki-NG for developing and implementing.

Set Up Development Environment for Contiki

To build a Contiki application, we need to prepare our development environment. Currently, the Contiki development environment can be deployed on the Linux platform. There are two methods: instant Contiki and manual installation. Then, we will set up a Contiki-NG development environment.

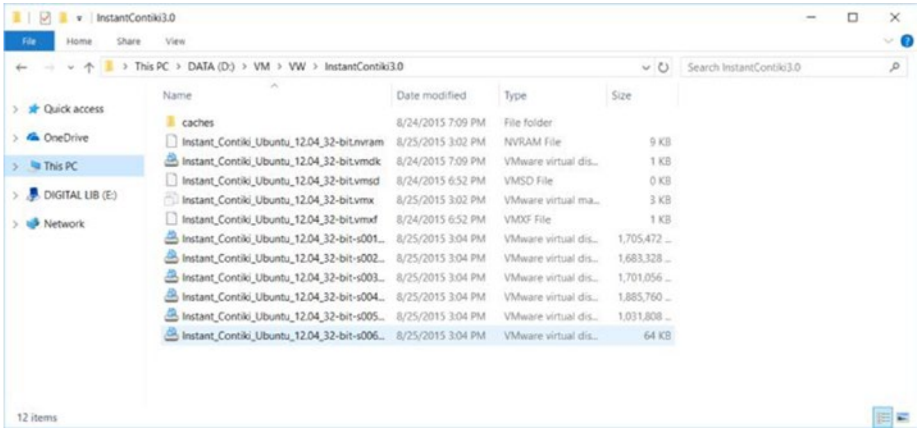
We will review deployment for both Contiki and Contiki-NG in the next section.

Instant Contiki

Contiki provides a complete development environment under Ubuntu Linux that is available in virtual-machine form. This approach is easy and low risk without breaking your current OS.

Follow these steps:

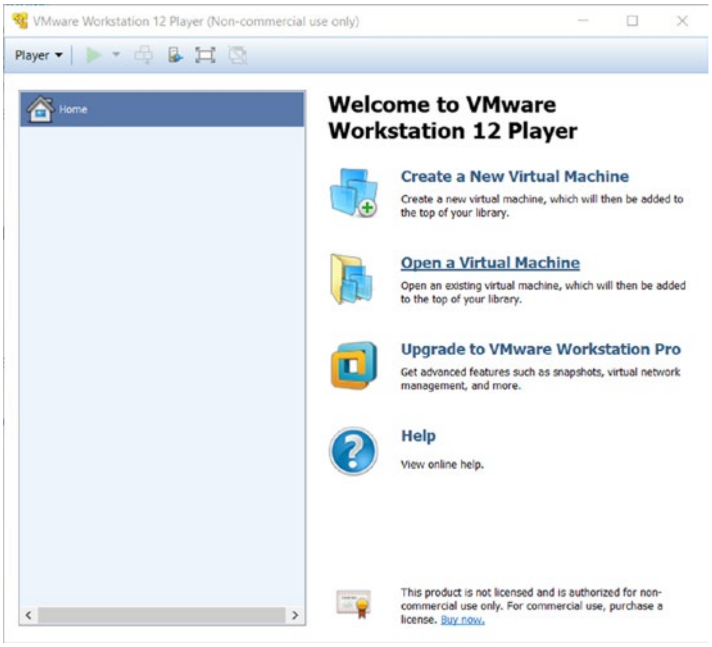
- Download instant Contiki from `http://sourceforge.net/projects/contiki/files/Instant%20Contiki/`.
- Download VMWare Workstation player (Free) or VMWare Workstation (not free). For VMWare player, you can download it from `http://www.vmware.com/go/downloadplayer/`. You can also use Virtualbox instead of VMWare.
- After downloading Instant Contiki, you can extract it to a specific folder. You should see some files as shown in Figure 1-11.



Name	Date modified	Type	Size
caches	8/24/2015 7:09 PM	File folder	
Instant_Contiki_Ubuntu_12.04_32-bit.nvram	8/25/2015 3:02 PM	NVRAM File	9 KB
Instant_Contiki_Ubuntu_12.04_32-bit.vmdk	8/24/2015 7:09 PM	VMware virtual dis...	1 KB
Instant_Contiki_Ubuntu_12.04_32-bit.vmsd	8/24/2015 6:52 PM	VMSD File	0 KB
Instant_Contiki_Ubuntu_12.04_32-bit.vmx	8/25/2015 3:02 PM	VMware virtual ma...	3 KB
Instant_Contiki_Ubuntu_12.04_32-bit.vmxf	8/24/2015 6:52 PM	VMXF File	1 KB
Instant_Contiki_Ubuntu_12.04_32-bit-s001...	8/25/2015 3:04 PM	VMware virtual dis...	1,705,472 ...
Instant_Contiki_Ubuntu_12.04_32-bit-s002...	8/25/2015 3:04 PM	VMware virtual dis...	1,683,328 ...
Instant_Contiki_Ubuntu_12.04_32-bit-s003...	8/25/2015 3:04 PM	VMware virtual dis...	1,701,056 ...
Instant_Contiki_Ubuntu_12.04_32-bit-s004...	8/25/2015 3:04 PM	VMware virtual dis...	1,885,760 ...
Instant_Contiki_Ubuntu_12.04_32-bit-s005...	8/25/2015 3:04 PM	VMware virtual dis...	1,031,808 ...
Instant_Contiki_Ubuntu_12.04_32-bit-s006...	8/25/2015 3:04 PM	VMware virtual dis...	64 KB

Figure 1-11. *Extracted instant Contiki files*

VMWare Workstation Player is free. It is available for Windows and Linux. For Mac users, there is no free VMWare Workstation Player. You can use VMWare Fusion. I have installed VMWare Workstation Player on Windows 10. You can see it in Figure 1-12.



Welcome to VMware Workstation 12 Player

Create a New Virtual Machine

Create a new virtual machine, which will then be added to the top of your library.

Open a Virtual Machine

Open an existing virtual machine, which will then be added to the top of your library.

Upgrade to VMware Workstation Pro

Get advanced features such as snapshots, virtual network management, and more.

Help

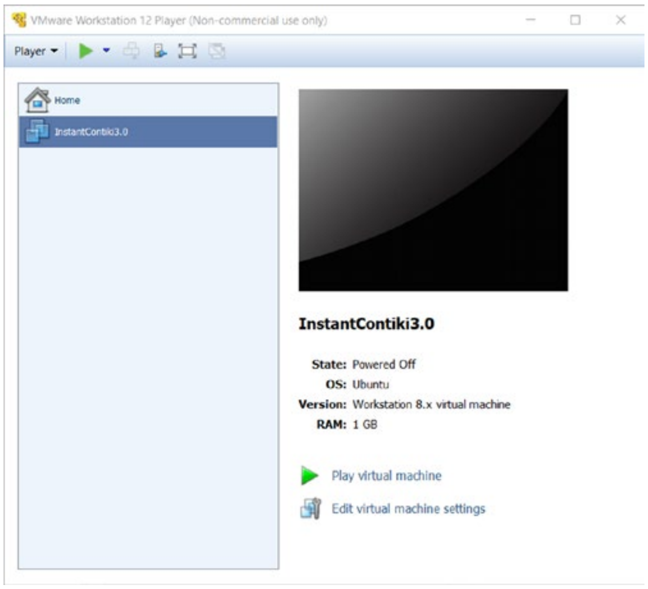
View online help.

This product is not licensed and is authorized for non-commercial use only. For commercial use, purchase a license. Buy now.

Figure 1-12. *VMWare Workstation player 12 on Windows 10*

Now, you can open Instant Contiki using VMWare Workstation Player by clicking **Open a Virtual Machine**. Navigate to the `*.vmdk` file in the folder to which Instant Contiki file was extracted.

After this succeeds, you can see Instant Contiki on VMWare Workstation Player, as shown in Figure 1-13.

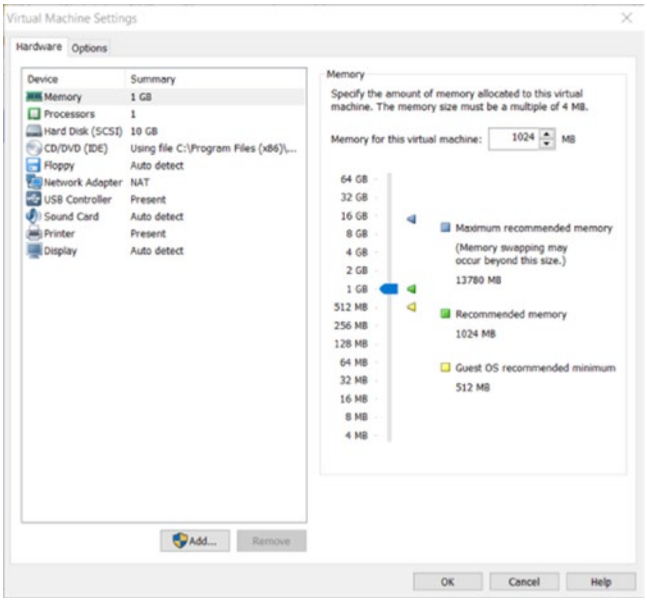

VMware Workstation 12 Player (Non-commercial use only)
Player
Home
InstantContiki3.0
Play virtual machine
Edit virtual machine settings

InstantContiki3.0

State: Powered Off
OS: Ubuntu
Version: Workstation 8.x virtual machine
RAM: 1 GB

Figure 1-13. *Instant Contiki has loaded on VMWare Workstation Player*

By default, Instant Contiki is configured to use 1GB RAM. You can customize this by clicking **Edit virtual machine settings**. You should get a dialog as shown in Figure 1-14.


Virtual Machine Settings

Hardware | Options

Device	Summary
Memory	1 GB
Processors	1
Hard Disk (SCSI)	10 GB
CD/DVD (IDE)	Using file C:\Program Files (x86)\...
Floppy	Auto detect
Network Adapter	NAT
USB Controller	Present
Sound Card	Auto detect
Printer	Present
Display	Auto detect

Memory

Specify the amount of memory allocated to this virtual machine. The memory size must be a multiple of 4 MB.

Memory for this virtual machine: 1024 MB

Maximum recommended memory (Memory swapping may occur beyond this size.) 13780 MB

Recommended memory 1024 MB

Guest OS recommended minimum 512 MB

Figure 1-14. *Customizing Instant Contiki*

Since my computer has 16GB of RAM, I set my Instant Contiki with 4GB of RAM. If you are done, click the OK button to save and close the dialog.

Now, you can run Instant Contiki by clicking **Play virtual machine**; you should see the Ubuntu desktop. You can see it in Figure 1-15.

If your WSN mote has an MSP430-based MCU such as Sky and Telosb, you should install the ggc-msp430 library in order to develop your Contiki application. You can type this command in Ubuntu Terminal:

```
$ sudo apt-get install gcc-msp430
```

Your virtual machine is ready for Contiki development.

Figure 1-15. *Contiki OS is running on VMWare Workstation Player*

Troubleshooting

If you are running VMWare Workstation Player on Windows 8.1/10 or later, you may get problems due to conflicts with Hyper-V. Since VMWare Workstation and Hyper-V cannot run together on one computer, you should uninstall and disable Hyper-V on Windows 8.1/10.

From my experience, I use Windows 10 with installed Hyper-V. When I use the VMWare application, I disable my Hyper-V. You do so using command prompts with the Administrator level. Type this command:

```
$ bcdedit /set hypervisorlaunchtype off
```

Then, you can restart Windows.

If you want to reenable Hyper-V, you can type this command:

```
$ bcdedit /set hypervisorlaunchtype on
```

Manual Installation

If you have a computer with installed Linux, you can install the Contiki development environment on your platform.

First, you should install all required libraries to run Contiki OS. You can type these commands in Terminal:

```
$ sudo apt-get update
$ sudo apt-get install build-essential
$ sudo apt-get install git
$ sudo apt-get install binutils-msp430 gcc-msp430 msp430-libc
msp430mcu mspdebug gcc-arm-none-eabi gdb-arm-none-eabi
```

You also need the Java run-time and SDK to run the Contiki OS simulator. In this case, we use Open JDK. You can use Java from Oracle. Type this command:

```
$ sudo apt-get install openjdk-8-jdk openjdk-8-jre ant
libncurses5-dev
```

Since Contiki OS runs a 32-bit environment, if you have Linux OS with 64-bit, you can install these libraries:

```
$ sudo apt-get install lib32ncurses5
```

Now, you can download the Contiki OS source code. Open Terminal and navigate to the specific folder where Contiki OS files will be extracted:

```
$ git clone https://github.com/contiki-os/contiki
```

Your computer is ready for Contiki OS development.

Set Up Contiki-NG Development Environment

Currently, Contiki-NG does not provide an Instant Contiki, so it must be installed manually. The installation process can be found here: `https://github.com/contiki-ng/contiki-ng/wiki/Toolchain-installation`.

In general, setting up Contiki-NG can be done with the following steps:

- Install required libraries.
- Install compiler and its dependences for specific hardware platform.
- Download and configure Contiki-NG.

The first step to deploy Contiki-NG is to install all required libraries for development. In this section, I use Ubuntu Linux for development testing. I use Ubuntu LTS 16.04 with x64 platform. Type these commands on Linux Terminal to install libraries:

```
$ sudo apt update
$ sudo apt install build-essential doxygen git curl wireshark
python-serial
```

While you are installing Wireshark, you should enable the feature that allows non-superuser capture packets (select "yes"). Add your account into the `wireshark` group. You can type this command, substituting <user> with your Linux account:

```
$ sudo usermod -a -G wireshark <user>
```

The next step is to install the compiler and its dependencies, based on the Contiki mote hardware. If you have a Contiki mote based on MSP430, you can install the compiler and libraries for MSP430. You can type this command:

```
$ sudo apt install gcc-msp430
```

If you want to install the latest version of the MSP430 compiler, you can read how at `https://github.com/tecip-nes/contiki-tres/wiki/Building-the-latest-version-of-mspgcc`.

For Contiki mote–based ARMs such as CC2538DK and Zoul, you can install the ARM compiler by typing these commands:

```
$ sudo add-apt-repository ppa:team-gcc-arm-embedded/ppa
$ sudo apt update
$ sudo apt install srecord gcc-arm-embedded
```

We also install JDK and Ant for the Contiki simulator, COOJA, that are built from Java. You can install these libraries by typing this command:

```
$ sudo apt install default-jdk ant
```

If you have several Java versions within Linux, you should set your Java preference. It is done by calling `update-alternatives`:

```
$ update-alternatives --config java
```

Cooja needs to have the environment variable `JAVA_HOME` set to work with native Contiki motes. You should set `JAVA_HOME` with the path found above in the `.profile` file:

```
$ echo 'export JAVA_HOME="/usr/lib/jvm/default-java"'>
~/.profile
```

Most Contiki motes are attached to the computer via USB. When we access them, we probably need administrator privileges. To be able to access the USB without using the administrator level, your account should be part of the groups `plugdev` and `dialout`. You add them by typing these commands. Be sure to change <user> to your Linux account:

```
$ sudo usermod -a -G plugdev <user>
$ sudo usermod -a -G dialout <user>
```

This is the case for an x64 platform. You probably will get an error when connecting via serial communication on a serial tool from Contiki-NG. You can install the following required libraries:

```
$ sudo apt-get update
$ sudo apt-get install lib32ncurses5 lib32z1
```

After finishing all tasks, you can reboot your computer.

Now, you can download Contiki-NG by cloning using git. Perform the following commands in Terminal:

```
$ git clone https://github.com/contiki-ng/contiki-ng.git
$ cd contiki-ng/
$ git submodule update --init --recursive
```

Now, you are ready to develop Contiki-NG.

Connect WSN Hardware to Computer

After all required libraries for Contiki are installed, you can connect the WSN hardware to the computer. Depending on the WSN hardware model, your WSN mote should be recognized by the computer. Some WSN hardware may need a hardware driver so your computer detects it. You can see my WSN mote, TelosB, connected to the computer in Figure 1-16.

After connecting to the WSN mote, you can verify whether the WSN mote is recognized by the computer. Type this command:

```
$ ls /dev/ttyUSB*
```

If your mote isn’t recognized by the computer, it's probably detected as `/dev/ttyACM*`.

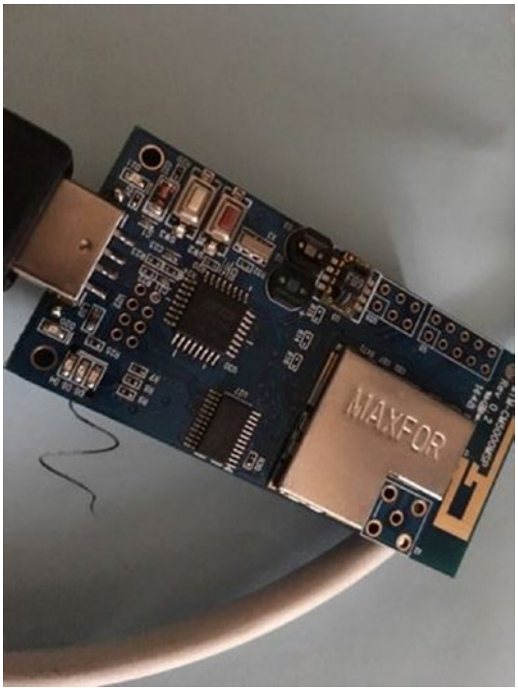
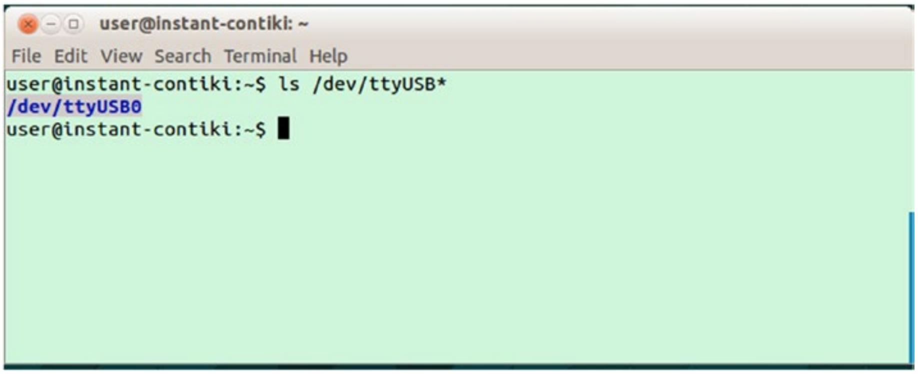


Figure 1-16. *TelosB mote is connected to computer through USB cable*

This program will query all connected WSN motes on your computer. If found, it will display a list of serial ports from WSN motes. You can see my WSN mote in Figure 1-17.

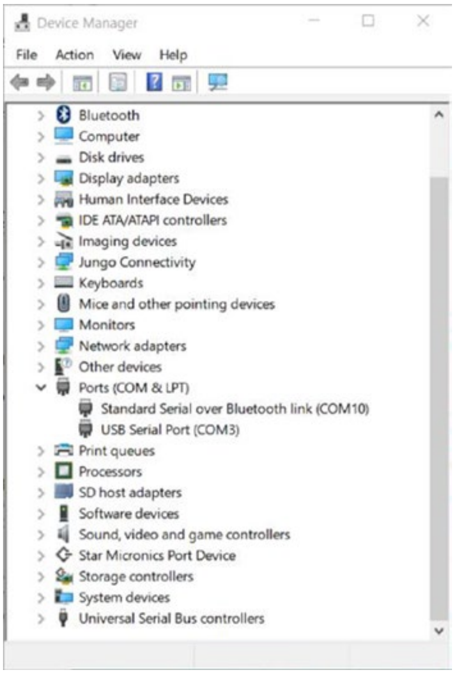


```
user@instant-contiki:~$ ls /dev/ttyUSB*
/dev/ttyUSB0
user@instant-contiki:~$ 
```

Figure 1-17. *WSN mote is detected on /dev/ttyUSB0*

If you use Instant Contiki, your WSN mote may be detected on Host OS. For instance, I use Windows 10 to run Instant Contiki. The detected WSN mote can be viewed on Device Manager, shown in Figure 1-18.

To connect a WSN mote from the host computer to a virtual machine on VMWare, you should transfer to a virtual machine. Since the hardware USB can only attach to one computer, the host computer can't access the WSN mote while it is being used by Ubuntu on the virtual machine.



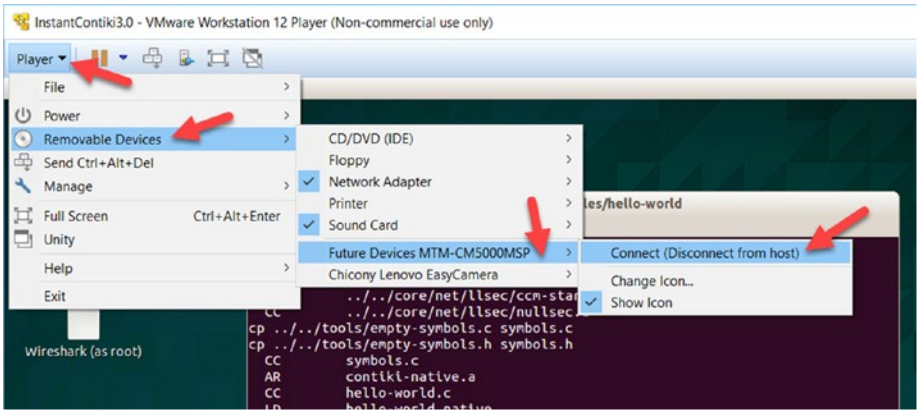
Device Manager

File Action View Help

- Bluetooth
- Computer
- Disk drives
- Display adapters
- Human Interface Devices
- IDE ATA/ATAPI controllers
- Imaging devices
- Jungo Connectivity
- Keyboards
- Mice and other pointing devices
- Monitors
- Network adapters
- Other devices
- Ports (COM & LPT)
  - Standard Serial over Bluetooth link (COM10)
  - USB Serial Port (COM3)
- Print queues
- Processors
- SD host adapters
- Software devices
- Sound, video and game controllers
- Star Micronics Port Device
- Storage controllers
- System devices
- Universal Serial Bus controllers

Figure 1-18. *WSN mote is detected by Device Manager*

How to transfer a WSN mote from the host to a virtual machine? You can click menu Player ➤ Removeable Devices ➤ <WSN_mote_name> ➤ Connect. You can see it in Figure 1-19.


InstantContiki3.0 - VMware Workstation 12 Player (Non-commercial use only)
Player
File
Power
Removable Devices
Send Ctrl+Alt+Del
Manage
Full Screen Ctrl+Alt+Enter
Unity
Help
Exit
CD/DVD (IDE)
Floppy
Network Adapter
Printer
Sound Card
Future Devices MTM-CM5000MSP
Chicony Lenovo EasyCamera
Connect (Disconnect from host)
Change Icon...
Show Icon
es/hello-world
Wireshark (as root)

```
          ../../core/net/llsec/ccm-star
  CC      ../../core/net/llsec/nullsec
cp ../../tools/empty-symbols.c symbols.c
cp ../../tools/empty-symbols.h symbols.h
  CC      symbols.c
  AR      contiki-native.a
  CC      hello-world.c
```

Figure 1-19. *Connect WSN mote from Ubuntu in virtual machine*

After connecting, you can perform Contiki development as usual on Ubuntu. You can verify the connected mote using Terminal.

Contiki and Raspberry Pi

Raspberry Pi is a very small computer. This board can run several operating systems. There are many Raspberry Pi models that you can use for development. The official OS is Raspbian OS, which is based on Debian Linux.

To deploy Contiki on Raspberry Pi, I recommend you use Raspbian OS for your board. Then, you can install Contiki manually without Instant Contiki since Raspberry Pi has limited RAM. Raspberry Pi has USB connectors so our WSN mote can be attached to the board. You can see my TelosB that is attached to a Raspberry Pi in Figure 1-20.

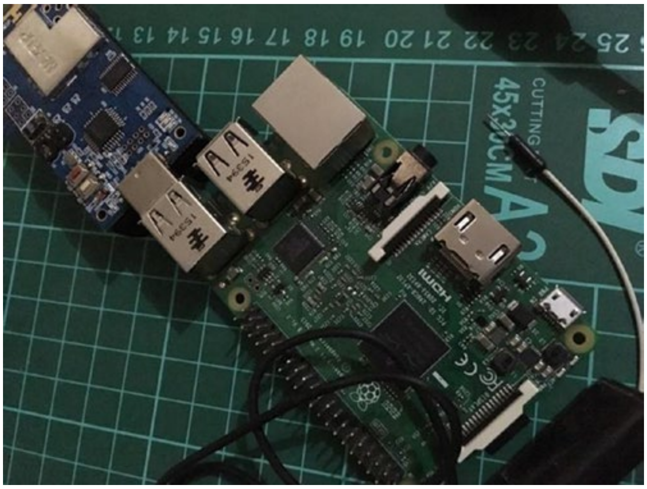


Figure 1-20. *Attach WSN mote to a Raspberry Pi*

Hello World Application for Contiki

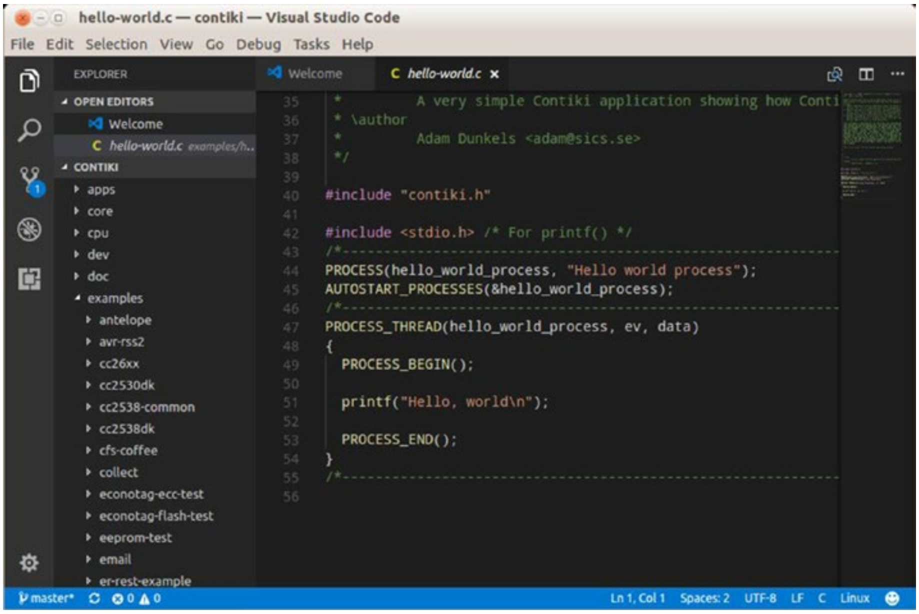
In this section, we will learn to build the first program for Contiki. We use the existing program sample from Contiki or Contiki-NG. It's a hello-world program, which is located in the `<contiki_folder>/examples/hello-world` folder. The Hello World program displays simple words—"Hello, world"—in the WSN mote's Terminal. This program consists of `hello-world.c` and `Makefile` files. After the program is compiled, you should see several files, such as `*.obj` and `*.hex` files.

To write a C program, use your favorite editor, such as vi, vim, and nano. Also, use a visual editor; for instance, Eclipse, Sublime Text, and Visual Studio Code. I use Visual Studio from Microsoft. You can download it on `https://code.visualstudio.com`. It is available for Linux, Mac, and Windows. Figure 1-21 shows Visual Studio Code to open the Blink application.

To start to write a Contiki program from scratch, you create a folder called `hello-world`. Then, you create `hello-world.c` within the `hello-world` folder. You also can run a program sample, `hello-world`, from `<contiki_folder>/examples/hello-world` folder. Navigate to your Terminal and then build that program.

If you want to build a project from scratch, you must continue your development. The following is the complete code for the `hello-world.c` file.

```
include "contiki.h"

#include <stdio.h> /* For printf() */
/*---------------------------------------------------------------*/
PROCESS(hello_world_process, "Hello world process");
AUTOSTART_PROCESSES(&hello_world_process);
/*---------------------------------------------------------------*/
PROCESS_THREAD(hello_world_process, ev, data)
{
  PROCESS_BEGIN();

  printf("Hello, world\n");

  PROCESS_END();
}
```



```
 *          A very simple Contiki application showing how Conti
 * \author
 *          Adam Dunkels <adam@sics.se>
 */

#include "contiki.h"

#include <stdio.h> /* For printf() */
/*---------------------------------------------------------------------------*/
PROCESS(hello_world_process, "Hello world process");
AUTOSTART_PROCESSES(&hello_world_process);
/*---------------------------------------------------------------------------*/
PROCESS_THREAD(hello_world_process, ev, data)
{
  PROCESS_BEGIN();

  printf("Hello, world\n");

  PROCESS_END();
}
/*---------------------------------------------------------------------------*/
```

Figure 1-21. *Visual Studio code on Ubuntu Linux*

Explanation

This program declares a Contiki process thread, called `hello_world_process`. To print message to Terminal, use the `printf()` function:

```
PROCESS_THREAD(hello_world_process, ev, data)
{
  PROCESS_BEGIN();

  printf("Hello, world\n");

  PROCESS_END();
}
```

`hello_world_process` will be executed automatically using `AUTOSTART_PROCESSES()`.

```
PROCESS(hello_world_process, "Hello world process");
```

AUTOSTART_PROCESSES(&hello_world_process);

Last, you should make a `Makefile` file. The following is the content of the `Makefile` file:

```
CONTIKI_PROJECT = hello-world
all: $(CONTIKI_PROJECT)

CONTIKI = /home/user/Documents/book/contiki
include $(CONTIKI)/Makefile.include
```

Three items are required in our `Makefile` file, which are described as follows:

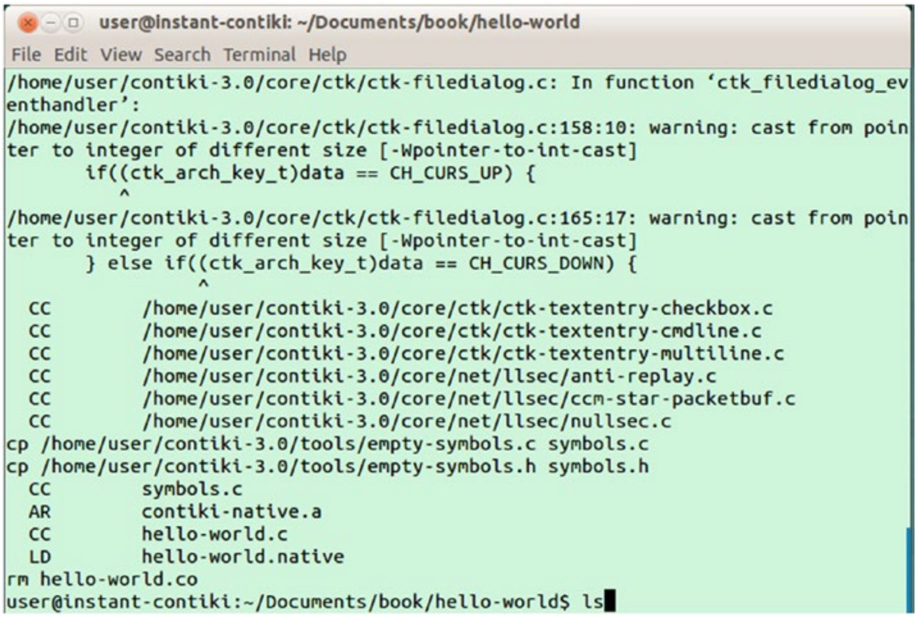
- `CONTIKI_PROJECT` is used to declare our project name.
- `CONTIKI` is a Contiki root directory where Contiki libraries are.
- We include `$(CONTIKI)/Makefile.include` file in our program.

Change `CONTIKI` for your Contiki root folder where the Contiki source code files, `https://github.com/contiki-os/contiki` or `https://github.com/contiki-ng/` for Contiki-NG, are located.

If all required program setup is done, we can compile C program using `make` by passing in the WSN platform. For our demo, we use the native app as the target, so we pass `native` while compiling:

```
$ make TARGET=native
```

This compiling generates a `<project_name>.native` binary file. You can see it in Figure 1-22. A `hello-world.native` file is generated.


user@instant-contiki: ~/Documents/book/hello-world
File Edit View Search Terminal Help

```
/home/user/contiki-3.0/core/ctk/ctk-filedialog.c: In function ‘ctk_filedialog_ev
enthandler’:
/home/user/contiki-3.0/core/ctk/ctk-filedialog.c:158:10: warning: cast from poin
ter to integer of different size [-Wpointer-to-int-cast]
       if((ctk_arch_key_t)data == CH_CURS_UP) {
          ^
/home/user/contiki-3.0/core/ctk/ctk-filedialog.c:165:17: warning: cast from poin
ter to integer of different size [-Wpointer-to-int-cast]
       } else if((ctk_arch_key_t)data == CH_CURS_DOWN) {
                 ^
  CC        /home/user/contiki-3.0/core/ctk/ctk-textentry-checkbox.c
  CC        /home/user/contiki-3.0/core/ctk/ctk-textentry-cmdline.c
  CC        /home/user/contiki-3.0/core/ctk/ctk-textentry-multiline.c
  CC        /home/user/contiki-3.0/core/net/llsec/anti-replay.c
  CC        /home/user/contiki-3.0/core/net/llsec/ccm-star-packetbuf.c
  CC        /home/user/contiki-3.0/core/net/llsec/nullsec.c
cp /home/user/contiki-3.0/tools/empty-symbols.c symbols.c
cp /home/user/contiki-3.0/tools/empty-symbols.h symbols.h
  CC        symbols.c
  AR        contiki-native.a
  CC        hello-world.c
  LD        hello-world.native
rm hello-world.co
user@instant-contiki:~/Documents/book/hello-world$ ls
```

Figure 1-22. *Compiling Contiki application on native target*

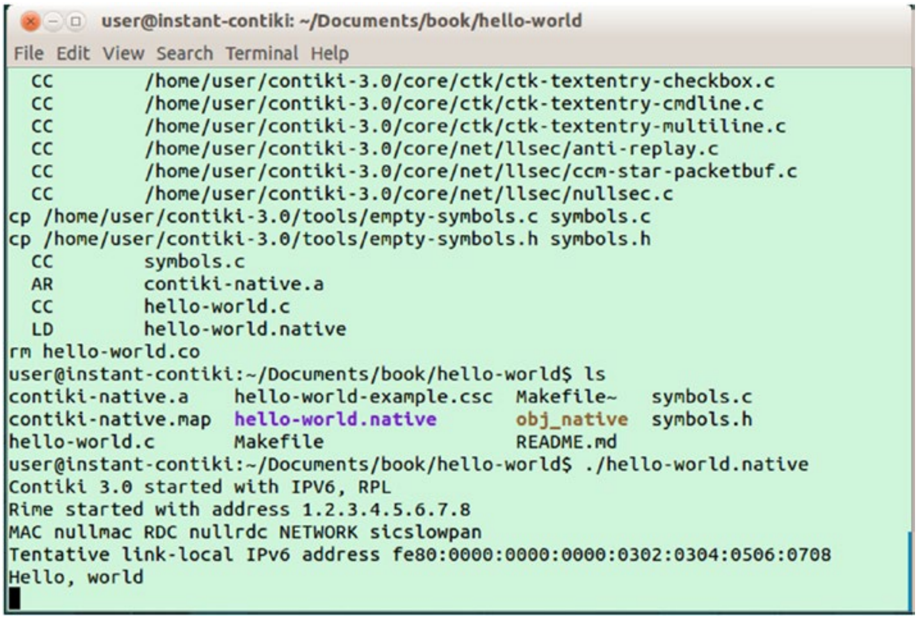
To run the Contiki app, you can type this command:

```
$ ./hello-world.native
```

If you get an error due to security issues, you probably need to run this program with administrator privilege. You can type this command:

```
$ sudo ./hello-world.native
```

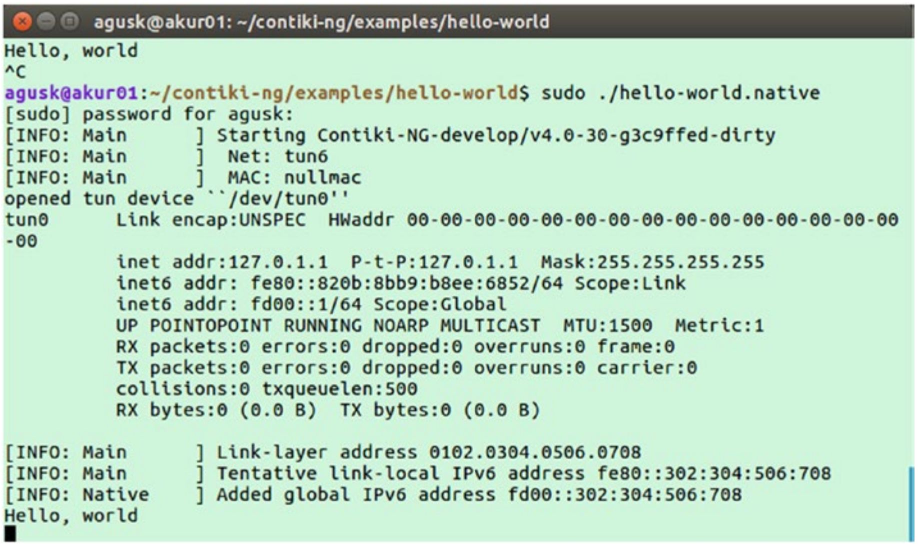
It shows THE IPv6 address and displays “Hello, world” in Terminal. You can see it in Figure 1-23(a) for Contiki app and (b) for Contiki-NG app. To stop your Contiki program, you can press CTRL+C.



user@instant-contiki: ~/Documents/book/hello-world
File Edit View Search Terminal Help

```
  CC        /home/user/contiki-3.0/core/ctk/ctk-textentry-checkbox.c
  CC        /home/user/contiki-3.0/core/ctk/ctk-textentry-cmdline.c
  CC        /home/user/contiki-3.0/core/ctk/ctk-textentry-multiline.c
  CC        /home/user/contiki-3.0/core/net/llsec/anti-replay.c
  CC        /home/user/contiki-3.0/core/net/llsec/ccm-star-packetbuf.c
  CC        /home/user/contiki-3.0/core/net/llsec/nullsec.c
cp /home/user/contiki-3.0/tools/empty-symbols.c symbols.c
cp /home/user/contiki-3.0/tools/empty-symbols.h symbols.h
  CC        symbols.c
  AR        contiki-native.a
  CC        hello-world.c
  LD        hello-world.native
rm hello-world.co
user@instant-contiki:~/Documents/book/hello-world$ ls
contiki-native.a    hello-world-example.csc  Makefile~    symbols.c
contiki-native.map  hello-world.native       obj_native   symbols.h
hello-world.c       Makefile                 README.md
user@instant-contiki:~/Documents/book/hello-world$ ./hello-world.native
Contiki 3.0 started with IPV6, RPL
Rime started with address 1.2.3.4.5.6.7.8
MAC nullmac RDC nullrdc NETWORK sicslowpan
Tentative link-local IPv6 address fe80:0000:0000:0000:0302:0304:0506:0708
Hello, world
```

(a) Contiki app



```
Hello, world
^C
agusk@akur01:~/contiki-ng/examples/hello-world$ sudo ./hello-world.native
[sudo] password for agusk:
[INFO: Main      ] Starting Contiki-NG-develop/v4.0-30-g3c9ffed-dirty
[INFO: Main      ]  Net: tun6
[INFO: Main      ]  MAC: nullmac
opened tun device ``/dev/tun0''
tun0      Link encap:UNSPEC  HWaddr 00-00-00-00-00-00-00-00-00-00-00-00-00-00
-00
          inet addr:127.0.1.1  P-t-P:127.0.1.1  Mask:255.255.255.255
          inet6 addr: fe80::820b:8bb9:b8ee:6852/64 Scope:Link
          inet6 addr: fd00::1/64 Scope:Global
          UP POINTOPOINT RUNNING NOARP MULTICAST  MTU:1500  Metric:1
          RX packets:0 errors:0 dropped:0 overruns:0 frame:0
          TX packets:0 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:500
          RX bytes:0 (0.0 B)  TX bytes:0 (0.0 B)

[INFO: Main      ] Link-layer address 0102.0304.0506.0708
[INFO: Main      ] Tentative link-local IPv6 address fe80::302:304:506:708
[INFO: Native    ] Added global IPv6 address fd00::302:304:506:708
Hello, world
```

(b) Contiki-NG app

Figure 1-23. *Running Contiki application as native, (a) Contiki app and (b) Contiki-NG app*

Next, we deploy the Contiki application to the Contiki hardware. For instance, I use TelosB as my WSN mote target. TelosB is a Sky platform from Contiki because TelosB uses MSP430 MCU.

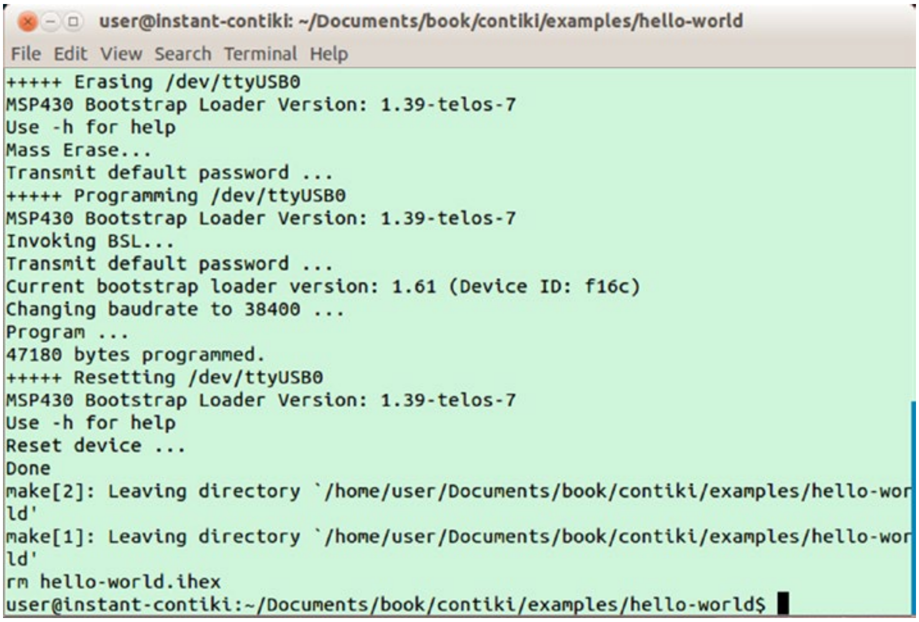
Before deploying the Contiki program to the Contiki mote, make sure your Contiki mote is already attached to your computer. For instance, my Contiki mote, TelosB, is detected as `/dev/ttyUSB0`. You can verify the attached Contiki mote using the following command:

```
$ ls /dev/ttyUSB*
```

Now, you can compile and save the target platform by typing this command:

```
$ make TARGET=sky
$ make TARGET=sky savetarget
```

A sample of the compiling output is shown in Figure 1-24.


user@instant-contiki: ~/Documents/book/contiki/examples/hello-world
File Edit View Search Terminal Help

```
+++++ Erasing /dev/ttyUSB0
MSP430 Bootstrap Loader Version: 1.39-telos-7
Use -h for help
Mass Erase...
Transmit default password ...
+++++ Programming /dev/ttyUSB0
MSP430 Bootstrap Loader Version: 1.39-telos-7
Invoking BSL...
Transmit default password ...
Current bootstrap loader version: 1.61 (Device ID: f16c)
Changing baudrate to 38400 ...
Program ...
47180 bytes programmed.
+++++ Resetting /dev/ttyUSB0
MSP430 Bootstrap Loader Version: 1.39-telos-7
Use -h for help
Reset device ...
Done
make[2]: Leaving directory `/home/user/Documents/book/contiki/examples/hello-wor
ld'
make[1]: Leaving directory `/home/user/Documents/book/contiki/examples/hello-wor
ld'
rm hello-world.ihex
user@instant-contiki:~/Documents/book/contiki/examples/hello-world$
```

Figure 1-24. *Flashing Contiki program to Sky platform on TelosB hardware*

This compiling will generate a `<project_name>.<platform>` file. In my case, this will generate a `hello-world.sky.ihex` file:

```
$ make hello-world.upload
```

If you get a permission error, you can run it using the administrator level:

```
$ sudo make hello-world.upload
```

This program will be flashed to Contiki hardware. It may take several minutes.

For Contiki-NG motes from Texas Instruments, you will probably get errors while uploading a program to the board. You can use SmartRF Flash Programmer. You can download it from `http://www.ti.com/tool/FLASH-PROGRAMMER`. Unfortunately, this tool currently only runs on Windows platforms.

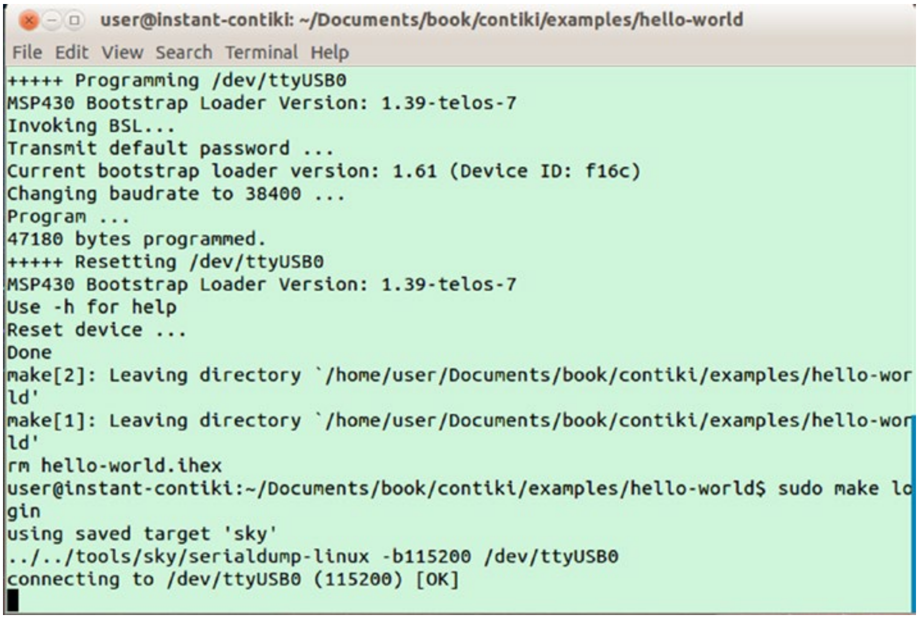
To see the program output from the Contiki hardware, we listen to incoming messages from the serial port of the Contiki hardware. You can type this command:

```
$ sudo make login
```

You also can specify a serial port of the Contiki hardware. For instance, Contiki hardware on serial port `/dev/ttyUSB0`. You can type this command:

```
$ sudo make MOTES=/dev/ttyUSB0 login
```

You can see the running Contiki program in Figure 1-25.

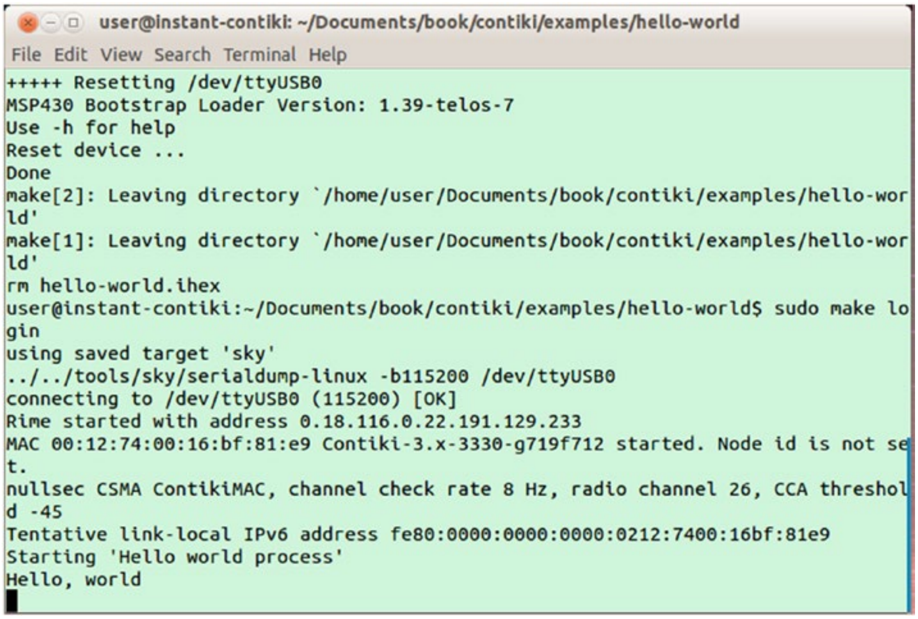

user@instant-contiki: ~/Documents/book/contiki/examples/hello-world
File Edit View Search Terminal Help

```
+++++ Programming /dev/ttyUSB0
MSP430 Bootstrap Loader Version: 1.39-telos-7
Invoking BSL...
Transmit default password ...
Current bootstrap loader version: 1.61 (Device ID: f16c)
Changing baudrate to 38400 ...
Program ...
47180 bytes programmed.
+++++ Resetting /dev/ttyUSB0
MSP430 Bootstrap Loader Version: 1.39-telos-7
Use -h for help
Reset device ...
Done
make[2]: Leaving directory `/home/user/Documents/book/contiki/examples/hello-wor
ld'
make[1]: Leaving directory `/home/user/Documents/book/contiki/examples/hello-wor
ld'
rm hello-world.ihex
user@instant-contiki:~/Documents/book/contiki/examples/hello-world$ sudo make lo
gin
using saved target 'sky'
../../tools/sky/serialdump-linux -b115200 /dev/ttyUSB0
connecting to /dev/ttyUSB0 (115200) [OK]
```

Figure 1-25. *Listening to messages from Contiki hardware*

You may not get any message from the hello-world program. Since this program runs the first process, we may miss this process. Try to reset the Contiki hardware so Contiki OS will reboot. Then, run the program.

It displays "Hello, world" in the listening program. You can see it in Figure 1-26. To stop your Contiki listening program, you can press CTRL+C.


user@instant-contiki: ~/Documents/book/contiki/examples/hello-world
File Edit View Search Terminal Help

```
+++++ Resetting /dev/ttyUSB0
MSP430 Bootstrap Loader Version: 1.39-telos-7
Use -h for help
Reset device ...
Done
make[2]: Leaving directory `/home/user/Documents/book/contiki/examples/hello-wor
ld'
make[1]: Leaving directory `/home/user/Documents/book/contiki/examples/hello-wor
ld'
rm hello-world.ihex
user@instant-contiki:~/Documents/book/contiki/examples/hello-world$ sudo make lo
gin
using saved target 'sky'
../../tools/sky/serialdump-linux -b115200 /dev/ttyUSB0
connecting to /dev/ttyUSB0 (115200) [OK]
Rime started with address 0.18.116.0.22.191.129.233
MAC 00:12:74:00:16:bf:81:e9 Contiki-3.x-3330-g719f712 started. Node id is not se
t.
nullsec CSMA ContikiMAC, channel check rate 8 Hz, radio channel 26, CCA threshol
d -45
Tentative link-local IPv6 address fe80:0000:0000:0000:0212:7400:16bf:81e9
Starting 'Hello world process'
Hello, world
```

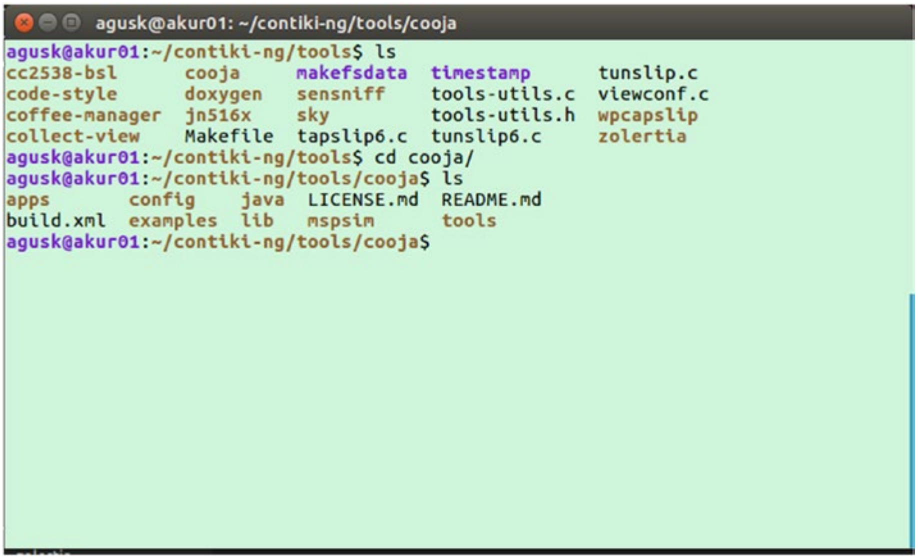
Figure 1-26. *Getting messages from Contiki hardware*

Contiki Simulator

If you don't have a WSN mote on which to run the Contiki program, you can use the Contiki simulator, COOJA. Although COOJA has limitations, it's still useful for reviewing and debugging. COOJA is a part of the Contiki tools. Its location is `<contiki_root>/tools/cooja`; see Figure 1-27. Further information about COOJA can be found at `https://github.com/contiki-os/contiki/wiki/An-Introduction-to-Cooja`.

In this section, we will set up COOJA. Then, we will run a simple Contiki program on COOJA.

Let's start.



```
agusk@akur01:~/contiki-ng/tools$ ls
cc2538-bsl      cooja     makefsdata  timestamp      tunslip.c
code-style      doxygen   sensniff    tools-utils.c  viewconf.c
coffee-manager  jn516x    sky         tools-utils.h  wpcapslip
collect-view    Makefile  tapslip6.c  tunslip6.c     zolertia
agusk@akur01:~/contiki-ng/tools$ cd cooja/
agusk@akur01:~/contiki-ng/tools/cooja$ ls
apps       config    java  LICENSE.md  README.md
build.xml  examples  lib   mspsim      tools
agusk@akur01:~/contiki-ng/tools/cooja$
```

Figure 1-27. *Contiki simulator, COOJA, path on Contiki-NG*

Setting Up

Before you run COOJA, you should configure your computer to update and check missing libraries for the COOJA application. Your computer should connect to the Internet.

You can configure COOJA by typing these commands:

```
$ cd /<contiki-ng_path>/tools/cooja
$ git submodule update --init
```

If this succeeds, you can run the COOJA application by typing this command:

```
$ ant run
```

You should get the COOJA application, shown in Figure 1-28.

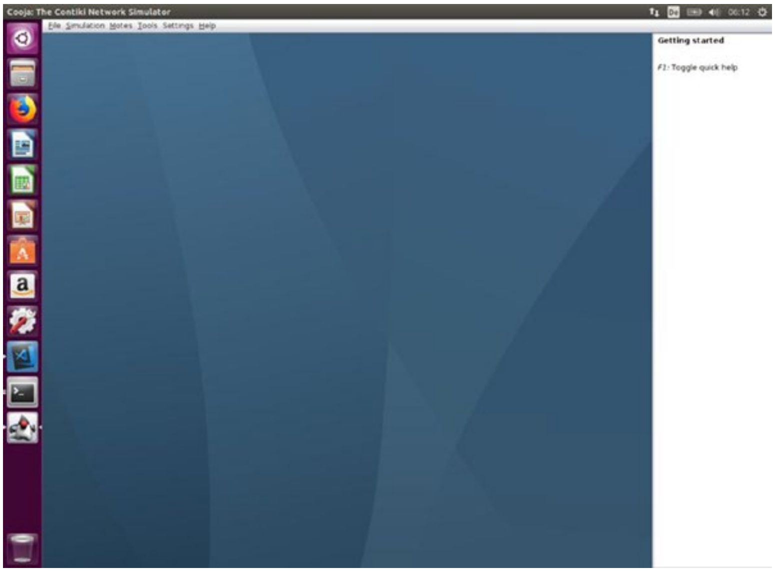

Cooja: The Contiki Network Simulator
File Simulation Motes Tools Settings Help
Getting started
F1: Toggle quick help

Figure 1-28. *Running COOJA for Contiki simulator*

Running Contiki Application

After you launch the COOJA application, you can run the Contiki application using COOJA. First, create a new simulation on COOJA. You can click File ➤ New simulation. You can see it in Figure 1-29.

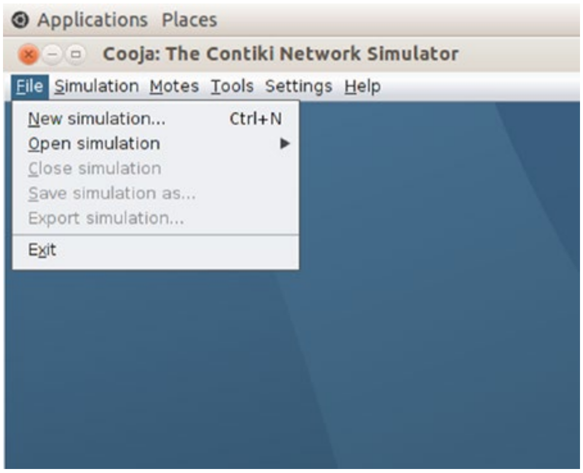
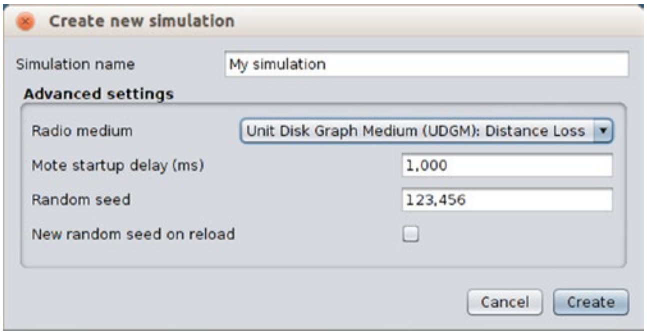


Figure 1-29. *Add a new simulation for Contiki*

You should get the dialog shown in Figure 1-30. Fill in the simulation name. If done, click the Create button.


Create new simulation

Simulation name: My simulation

Advanced settings

Radio medium: Unit Disk Graph Medium (UDGM): Distance Loss

Mote startup delay (ms): 1,000

Random seed: 123,456

New random seed on reload: ☐

Figure 1-30. *Filling in simulation name*

Now, you will get the Contiki simulator editor, COOJA, that is shown in Figure 1-31.

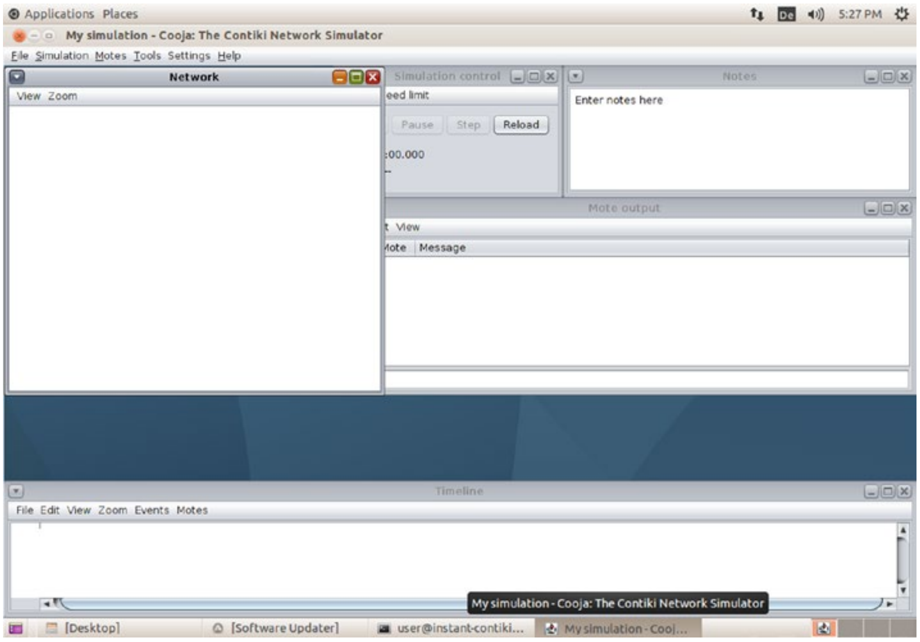


Figure 1-31. *Contiki simulator with Cooja*

The next step is to add the WSN motes on the simulator. You can do it by clicking menu Motes ➤ Add motes ➤ Mote platform (see Figure 1-32). Please select your Mote platform preference. For demo, I use Sky platform.

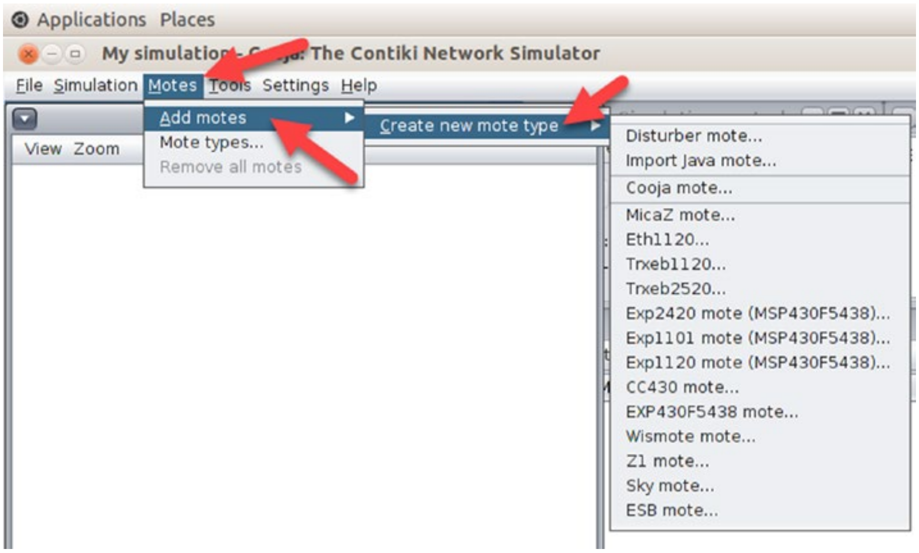
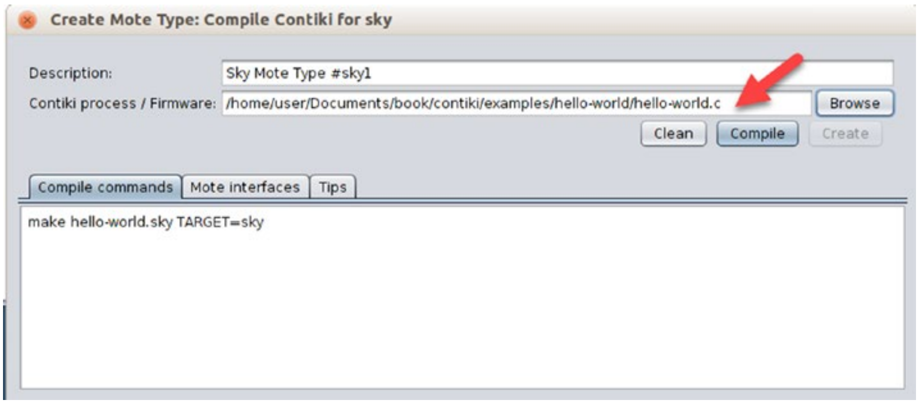


Figure 1-32. *Adding WSN motes*

Then, you will get the dialog shown in Figure 1-33. In the Contiki process/Firmware field, select your Contiki program. For demo purposes, we use the hello-world application. Select the `hello-world.c` file.

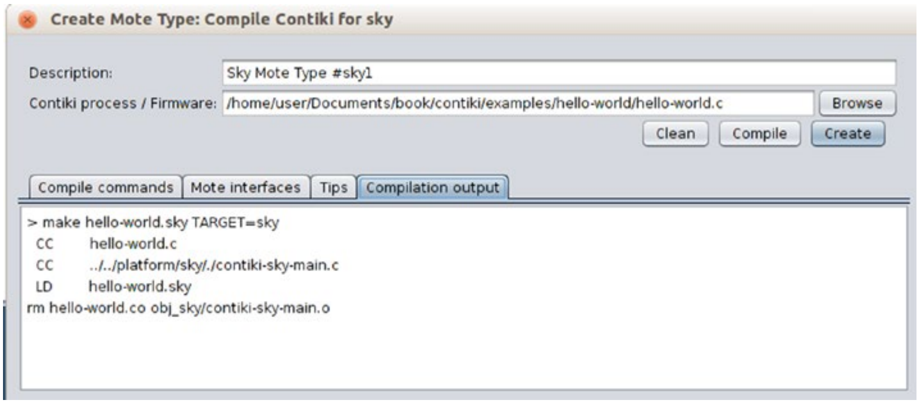

Create Mote Type: Compile Contiki for sky

Description: Sky Mote Type #sky1
Contiki process / Firmware: /home/user/Documents/book/contiki/examples/hello-world/hello-world.c

```
make hello-world.sky TARGET=sky
```

Figure 1-33. *Select Contiki program for running*

Compile the Contiki program by clicking the Compile button. You can see the sample of compilation output in Figure 1-34.


Create Mote Type: Compile Contiki for sky

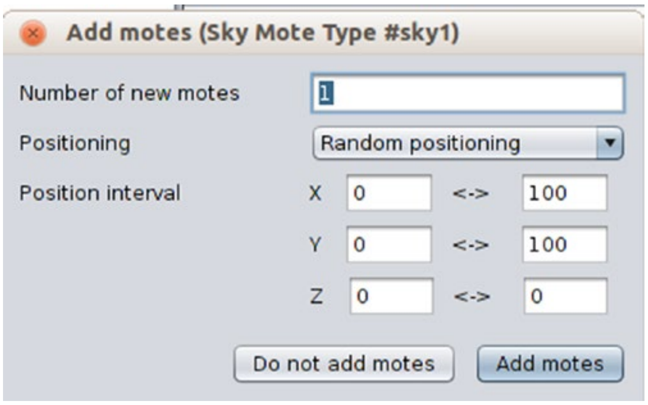
Description: Sky Mote Type #sky1

Contiki process / Firmware: /home/user/Documents/book/contiki/examples/hello-world/hello-world.c

```
> make hello-world.sky TARGET=sky
  CC        hello-world.c
  CC        ../../platform/sky/./contiki-sky-main.c
  LD        hello-world.sky
rm hello-world.co obj_sky/contiki-sky-main.o
```

Figure 1-34. *Compiling Contiki program on COOJA*

After compiling has completed, you will be asked to enter a number of WSN motes with their positions. For demo purposes, I fill in one WSN mote, as in Figure 1-35.


Add motes (Sky Mote Type #sky1)

Number of new motes	1			
Positioning	Random positioning			
Position interval	X	0	<->	100
	Y	0	<->	100
	Z	0	<->	0

Figure 1-35. *Filling in number of WSN motes*

If done, click the Add motes button.

Now you can see your motes in the network map. For instance, you can see my WSN mote in Figure 1-36.

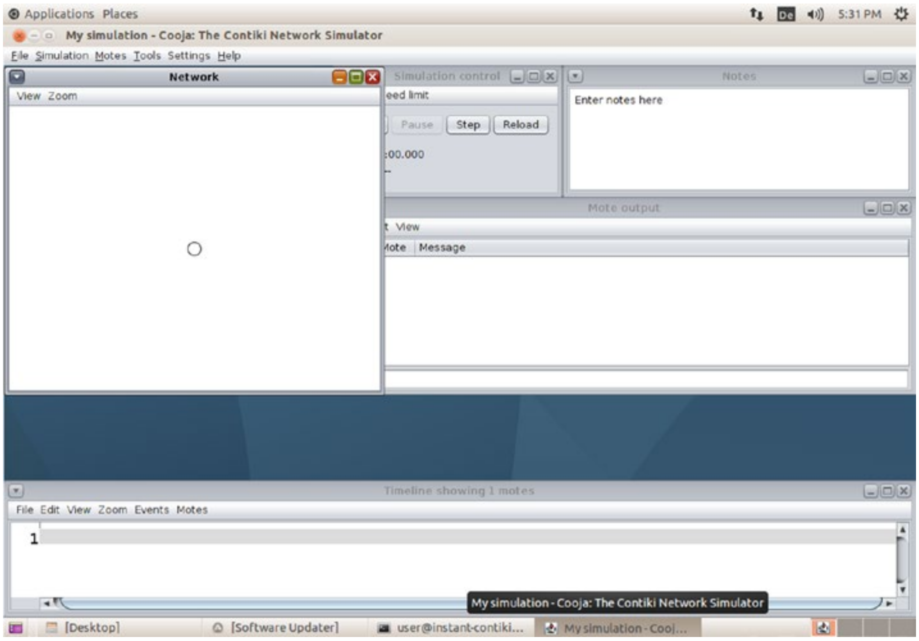


Figure 1-36. *A WSN mote on COOJA Contiki simulator*

To run the simulation, you can click the Start button on the Simulation Control dialog. See it in Figure 1-37.

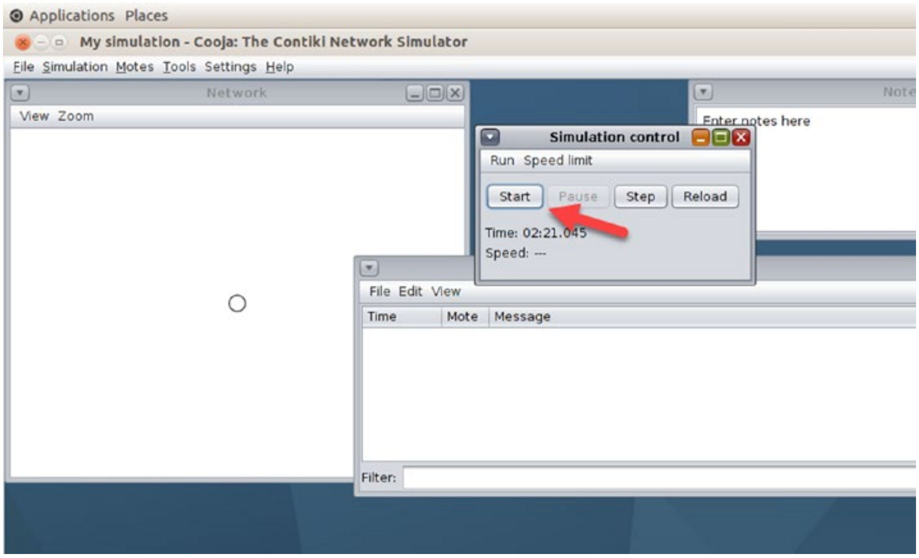
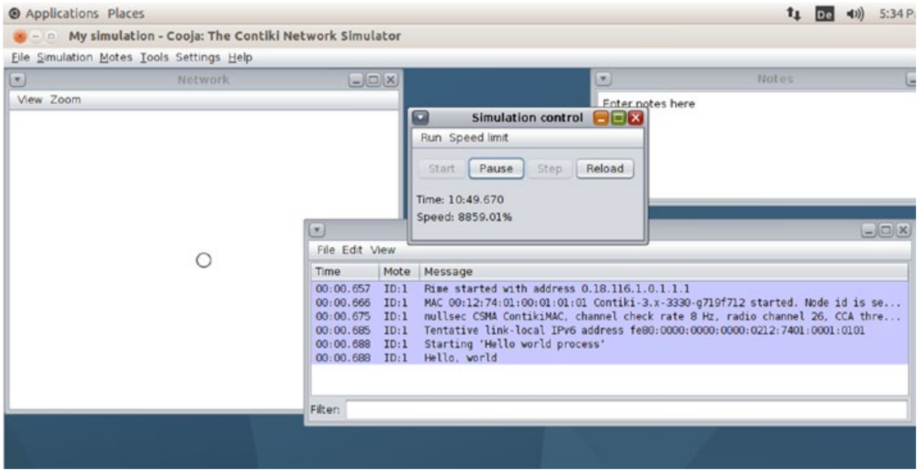


Figure 1-37. *Running Contiki simulator by clicking Start button*

After the Start button has been clicked, the Contiki program will run on COOJA. You should see the message “Hello, world” on the output panel. You can see it in Figure 1-38.



```
Time        Mote   Message
00:00.657   ID:1   Rime started with address 0.18.116.1.0.1.1.1
00:00.666   ID:1   MAC 00:12:74:01:00:01:01:01 Contiki-3.x-3330-g719f712 started. Node id is se...
00:00.675   ID:1   nullsec CSMA ContikiMAC, channel check rate 8 Hz, radio channel 26, CCA thre...
00:00.685   ID:1   Tentative link-local IPv6 address fe80:0000:0000:0000:0212:7401:0001:0101
00:00.688   ID:1   Starting 'Hello world process'
00:00.688   ID:1   Hello, world
```

Figure 1-38. *Running hello-world Contiki program on COOJA*

Debugging Contiki Application

Sometimes you want to trace your program after the program has been deployed into a WSN mote. In another scenario, you may want to investigate your Contiki program before deploying it to a WSN mote. Debugging is one solution for investigating your Contiki program.

In this section, you will learn various debugging methods with which to check your program. You can choose the best method that fits your case.

Hardware Debugger

Most WSN motes do not provide built-in hardware debuggers, so if you want to debug a Contiki-NG program through the hardware approach, you need additional hardware. Regarding what WSN mote model you want to perform debugging on, you should check your MCU model.

For Atmel MCU on MICAz, Mica2, and Iris platforms, you need JTAG Atmel. Otherwise, for MCU-based MSP430, you use MSP430 USB Debugging Interface from Texas Instruments (TI). This tool is shown in Figure 1-39 (source: `http://www.ti.com/tool/msp-fet`). You can buy it on this site: `http://www.ti.com/tool/msp-fet`.

Figure 1-39. *MSP430 USB debugging interface*

Hardware debuggers usually have capabilities in a remote debugger. For professional purposes, I recommend you use this tool.

LED Indicators

In general, a WSN mote is equipped with several LEDs. We can use these LEDs to indicate a specific task; for instance, we turn on a specific LED to inform us that the WSN mote performs sensing. You can find an LED library in the `<contiki>/core/dev/leds.h` header file. In the next chapter, we will try to develop a Contiki application utilizing GPIO (General Purpose Input/Output).

Based on my experience, this approach is easy to implement. The downside of this method is having no more information; for instance, you might want to get a certain value from a specific task on your program.

Debugging Using Contiki Simulator

With the third approach, you can use the Contiki simulator, COOJA. You can compile and attach a Contiki program to the Contiki simulator. You can see messages that are generated using the `printf()` method. For instance, the hello-world application prints messages using `printf()`.

The Contiki printf() Function

The last method that I like is using the `printf()` function. The idea is that our program writes messages using `printf()`, and then the messages will pass through to the serial port. To listen to incoming messages from the serial port, we can use the login command on Terminal.

This approach is easy and low cost for debugging your Contiki application. Just place a `printf()` function on the code you are investigating.

Summary

We have learned what Wireless Sensor Networks (WSN) and Contiki are. We also have set up Contiki and Contiki-NG development environments and run a sample program to the WSN mote and a simulator. Last, we learned how to debug the Contiki program.

In the next chapter, we will focus on the Contiki-NG programming language. We will learn how to build a Contiki-NG program and run it on Contiki-NG hardware and a simulator.

CHAPTER 2

Basic Contiki-NG Programming

Contiki-NG uses the C programming language to develop applications for WSN motes. In this chapter, you will learn this basic language for creating Contiki-NG programs. Program samples are provided to accelerate your learning speed.

The following is a list of topics that will be covered:

- Contiki-NG programming model
- Contiki-NG basic syntax
- reviewing protothreads
- extending the Contiki-NG library
- Contiki-NG coding conventions
- showing a demo for building a Contiki-NG application

Contiki-NG Programming Model

Contiki-NG uses the C programming language, which is component-driven. You build some components and then connect each component. Most WSN motes work in sleep mode. If there is any task to be executed, the program will perform the task through hardware interrupts. If the task is completed, the Contiki-NG program will go back to sleep mode.

© Agus Kurniawan 2018
A. Kurniawan, *Practical Contiki-NG*, https://doi.org/10.1007/978-1-4842-3408-2_2

Contiki-NG programming applies protothreads. In general, you can develop Contiki-NG applications using the approach shown in Figure 2-1. Start by creating a project. Then, create a C program and apply the protothreads approach for developing a Contiki-NG program. When finished writing the program, compile and upload it to the WSN mote.

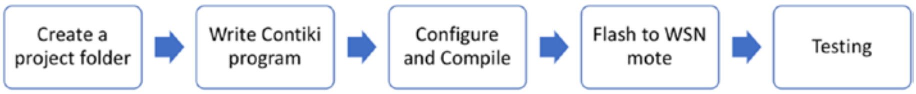


Figure 2-1. *Programming flow of a Contiki-NG program*

If you open the source code of Contiki-NG OS, you can see several folders, shown in Figure 2-2. Information about these folders can be read in Table 2-1.

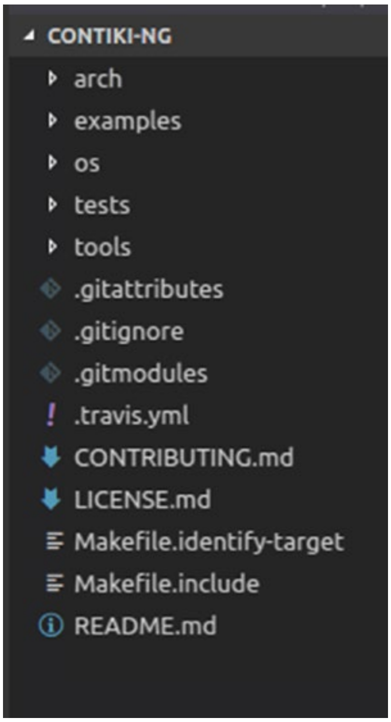


Figure 2-2. *Contiki-NG program structure*

Table 2-1. *Information for Contiki-NG OS Folders*

Folder	Description
arch	Contains CPU, platform, and dev for development
arch/cpu	Specific MCU information
arch/dev	External chip and devices
arch/platform	Specific files and platform drivers
os	Contiki-NG core files and libraries
tools	Tools for flashing, debugging, simulating
examples	Several Contiki-NG program samples
tests	Several test programs

In the next section, we will review the basics of C programming, such as the language syntax used to develop Contiki-NG programs.

Contiki-NG Basic Syntax

In general, Contiki-NG adopts the C programming language. In this section, we will review some C programming language basics. You can use any text editor to write C code.

Creating a Project

The Contiki-NG program does not provide project templates to build a program. If you want to create a new project, you start by creating a new folder and a `Makefile` file. Figure 2-3 shows a collection of Contiki-NG project samples.

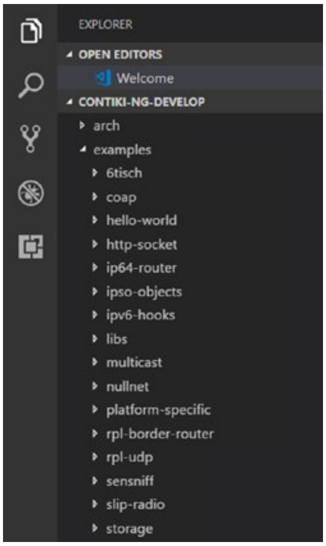


Figure 2-3. *A collection of Contiki-NG project samples*

You also can use program samples from the Contiki project (`https://github.com/contiki-os/contiki`). You should check if the one you choose is compatible with the Contiki-NG project (`https://github.com/contiki-ng/contiki-ng`).

Contiki-NG Basic Programming Language

Contiki-NG adopts the C general programming language for implementation. If you have experience in C programming, it won't require much effort to learn Contiki-NG programming. Contiki-NG programming is similar to C as far as declaring variables and using conditional statements and looping. You can see samples of the C programming language in Table 2-2.

***Table 2-2.** Basic Programming for C Language*

C Basic Programming	Example
Declare variables	`int num;`
	`int_t a, b, c;`
	`unsigned int isDone;`
Assign variables	`num = 3;`
	`isDone = 0;`
	`unsigned int m = 10;`
If-conditional	`if(running){`
	`  doSomething();`
	`}else {`
	`  perform();`
	`}`
Looping	`int len = 10;`
	`for(int i=0;i<len;i++) {`
	`  foo();`
	`}`
Comment codes	`// this comment`
	`/*`
	`this is also comment`
	`*/`

To improve your skills in the Contiki-NG programming language, I recommend you practice writing Contiki-NG programs.

Review Protothreads

Protothreads are lightweight threads designed for memory-constrained systems, such as small embedded systems or WSN nodes. You can see a protothreads implementation for Contiki-NG at `<contiki_root>/os/sys/pt.h`.

The following is the content of the `pt.h` file:

```
#ifndef PT_H_
#define PT_H_

#include "sys/lc.h"


struct pt {
  lc_t lc;
};

#define PT_WAITING 0
#define PT_YIELDED 1
#define PT_EXITED  2
#define PT_ENDED   3

#define PT_INIT(pt)   LC_INIT((pt)->lc)
#define PT_THREAD(name_args) char name_args
#define PT_BEGIN(pt) { char PT_YIELD_FLAG = 1; if (PT_YIELD_
FLAG) {;} LC_RESUME((pt)->lc)
#define PT_END(pt) LC_END((pt)->lc); PT_YIELD_FLAG = 0; \
                   PT_INIT(pt); return PT_ENDED; }
#define PT_WAIT_UNTIL(pt, condition)          \
  do {                                        \
    LC_SET((pt)->lc);                         \
    if(!(condition)) {                        \
      return PT_WAITING;                      \
    }                                         \
  } while(0)
#define PT_WAIT_WHILE(pt, cond)  PT_WAIT_UNTIL((pt), !(cond))
#define PT_WAIT_THREAD(pt, thread) PT_WAIT_WHILE((pt), PT_
SCHEDULE(thread))
#define PT_SPAWN(pt, child, thread)          \
  do {                                       \
    PT_INIT((child));                        \
    PT_WAIT_THREAD((pt), (thread));          \
  } while(0)
#define PT_RESTART(pt)                       \
  do {                                       \
    PT_INIT(pt);                             \
    return PT_WAITING;                       \
  } while(0)

#define PT_EXIT(pt)                          \
  do {                                       \
    PT_INIT(pt);                             \
    return PT_EXITED;                        \
  } while(0)

#define PT_SCHEDULE(f) ((f) < PT_EXITED)


#define PT_YIELD(pt)                         \
  do {                                       \
    PT_YIELD_FLAG = 0;                       \
    LC_SET((pt)->lc);                        \
    if(PT_YIELD_FLAG == 0) {                 \
      return PT_YIELDED;                     \
    }                                        \
  } while(0)
```

```
#define PT_YIELD_UNTIL(pt, cond)              \
  do {                                        \
    PT_YIELD_FLAG = 0;                        \
    LC_SET((pt)->lc);                         \
    if((PT_YIELD_FLAG == 0) || !(cond)) {     \
      return PT_YIELDED;                      \
    }                                         \
  } while(0)

#endif /* PT_H_ */
```

The following is a list of function descriptions based on the `pt.h` header:

- `PT_INIT(pt)` function is used to initialize a protothread.
- `PT_THREAD(name_args)` is a macro that is used to declare a protothread.
- `PT_BEGIN(pt)` is used to declare the starting point of a protothread.
- `PT_END(pt)` is used to end a protothread.
- `PT_WAIT_UNTIL(pt, condition)` is used for blocking the protothread until the specified condition is true.
- `PT_WAIT_WHILE(pt, cond)` is used for blocking and waiting while the condition is true.
- `PT_WAIT_THREAD(pt, thread)` is used to schedule a child protothread. The current protothread will block until the child protothread completes.
- `PT_SPAWN(pt, child, thread)` is used to spawn a child protothread and waits until it exits.

- `PT_RESTART(pt)` will block and cause the running protothread to restart its execution at the place of the `PT_BEGIN()` call.
- `PT_EXIT(pt)` is used to exit from a protothread.
- `PT_SCHEDULE(f)` is used to schedule a protothread. The return value of the function is non-zero if the protothread is running or zero if the protothread has exited.
- `PT_YIELD(pt)` yields from the current protothread.
- `PT_YIELD_UNTIL(pt, cond)` yields from the protothread until a condition occurs.

Extending the Contiki-NG Library

Contiki-NG OS consists of several libraries and apps that you can extend based on your case. To extend Contiki-NG OS functionalities, you can follow the same approach used while building C programs.

You add additional libraries by adding a C header and source code. Our Contiki-NG program will consume our libraries. For this demo, we create a header file called `mycounter.h` with the following code:

```
#ifndef MYCOUNTER_H
#define MYCOUNTER_H

int next_counter(int current);

#endif
```

This C header provides one function, next_counter(). This function will be implemented into the mycounter.c file. We perform a counterincrement with a maximum value of 99. You can write the complete code as follows:

```
#include "mycounter.h"

int next_counter(int current)
{
    if(current>99)
        current = 1;
    else
        current++;

    return current;
}
```

To access the extended library, we declare that header file. Then, we call library functions from our code. The following is a skeleton code sample to access the header file in a C program:

```
#include "mycounter.h"


...
static int counter = 0;

counter = next_counter(counter);
printf("Counter: %d\n", counter);
```

Next, we will implement our extended library and use it in a Contiki-NG program.

Contiki-NG Demo: Threading App

Now, we will try to build a Contiki-NG program that uses a header file. We create a folder called `demo-counter`. Then, we create several files as follows:

- `mycounter.h`
- `mycounter.c`
- `demo-counter.c`
- `Makefile`

You can see the project structure in Figure 2-4.

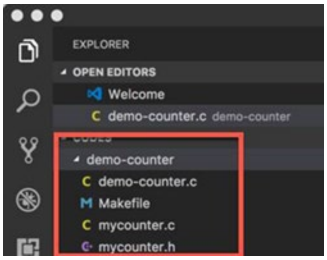


Figure 2-4. *Project structure for demo-counter project*

In this demo, we create a header file called `mycounter.h`. This C header provides one function, `next_counter()`, that generates an incremented number based on the input. The `next_counter()` function will be implemented into the `mycounter.c` file. In the previous section, we declared this library.

Next, we access `mycounter.h` in our main program. It's implemented in the `demo-counter.c` file. We use an event timer library from Contiki-NG, `etimer`. We generate an incremented number every three seconds.

The following is the complete code for `demo-counter.c`:

```
#include "contiki.h"
#include "sys/etimer.h"
#include "mycounter.h"

#include <stdio.h> /* For printf() */


PROCESS(counter_process, "Counter process");
AUTOSTART_PROCESSES(&counter_process);

static struct etimer timer;
static int counter = 0;

PROCESS_THREAD(counter_process, ev, data)
{
  PROCESS_BEGIN();

  printf("Demo Counter\n");
  while(1) {
    etimer_set(&timer, 3 * CLOCK_SECOND);
    PROCESS_WAIT_EVENT_UNTIL(etimer_expired(&timer));

    counter = next_counter(counter);
    printf("Counter: %d\n", counter);
  }

  PROCESS_END();
}
```

We also create a `Makefile` to configure our compiling. You can write these scripts for the `Makefile`. Change the `CONTIKI` value with your Contiki-NG root folder:

```
CONTIKI_PROJECT = demo-counter
all: $(CONTIKI_PROJECT)
```

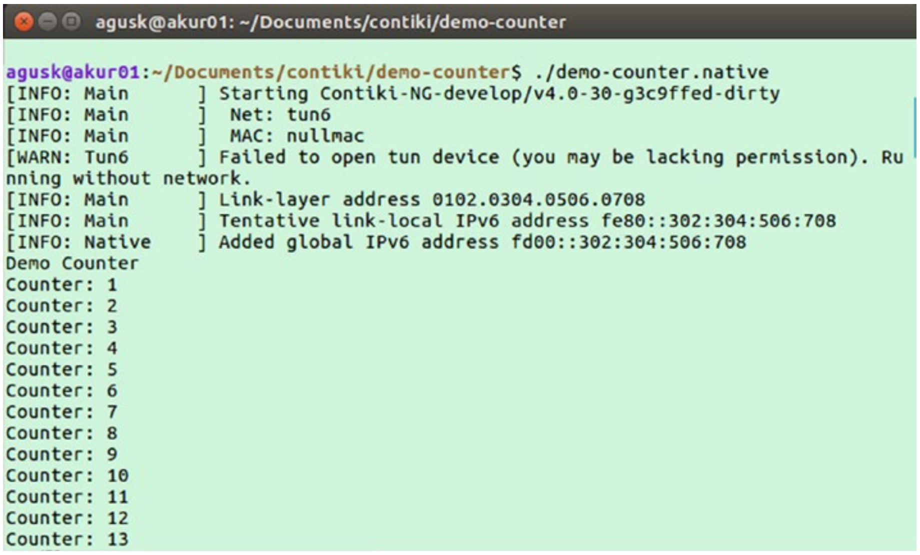
```
PROJECT_SOURCEFILES += mycounter.c

CONTIKI = /home/user/Documents/book/contiki
include $(CONTIKI)/Makefile.include
```

Save the program.

For testing, we run this program with a native target. You can open Terminal and navigate to the project folder. Then, you can compile and run the program. Type these commands:

```
$ make TARGET=native
$ ./demo-counter.native
```

If it succeeds, you will see an incremented number in Terminal. You can see a sample of the program output in Figure 2-5.



```
agusk@akur01: ~/Documents/contiki/demo-counter

agusk@akur01:~/Documents/contiki/demo-counter$ ./demo-counter.native
[INFO: Main      ] Starting Contiki-NG-develop/v4.0-30-g3c9ffed-dirty
[INFO: Main      ]  Net: tun6
[INFO: Main      ]  MAC: nullmac
[WARN: Tun6      ] Failed to open tun device (you may be lacking permission). Ru
nning without network.
[INFO: Main      ] Link-layer address 0102.0304.0506.0708
[INFO: Main      ] Tentative link-local IPv6 address fe80::302:304:506:708
[INFO: Native    ] Added global IPv6 address fd00::302:304:506:708
Demo Counter
Counter: 1
Counter: 2
Counter: 3
Counter: 4
Counter: 5
Counter: 6
Counter: 7
Counter: 8
Counter: 9
Counter: 10
Counter: 11
Counter: 12
Counter: 13
```

Figure 2-5. *Program output for demo-counter*

How does it work?

This program is simple. First, we declare our Contiki-NG process, `counter_process`. We also declare our event timer and number variable:

```
PROCESS(counter_process, "Counter process");
AUTOSTART_PROCESSES(&counter_process);

static struct etimer timer;
static int counter = 0;

PROCESS_THREAD(counter_process, ev, data)
{

}
```

Inside the `counter_process` function, we perform looping with the event timer. After raising an event, we call the `next_counter()` function to get an incremented number. Then, we print this value in Terminal:

```
PROCESS_THREAD(counter_process, ev, data)
{
  PROCESS_BEGIN();

  printf("Demo Counter\n");
  while(1) {
    etimer_set(&timer, 3 * CLOCK_SECOND);
    PROCESS_WAIT_EVENT_UNTIL(etimer_expired(&timer));

    counter = next_counter(counter);
    printf("Counter: %d\n", counter);
  }

  PROCESS_END();
}
```

Contiki-NG Coding Conventions

Imagine you're developing a program with a team of more than three developers. Each developer has a programming style and method. When the codes are merged, it may raise problems since the codes are not consistent in writing style. This problem could be solved if the code was written in the same style.

Contiki coding conventions are rules for a writing style. They consist of guidelines for how to write Contiki-NG programs. You can read the full coding conventions for Contiki at `https://github.com/contiki-os/contiki/blob/master/doc/code-style.C`.

Demo: Build Contiki-NG Application

In this section, we are going to develop a Contiki-NG application called virtual-sensor. We will use the general library for the sensor, which will be used for temperature and humidity readings. We will create a virtual sensor in a header file that exposes two functions, `read_temperature()` and `read_humidity()`. You can see this in Figure 2-6.

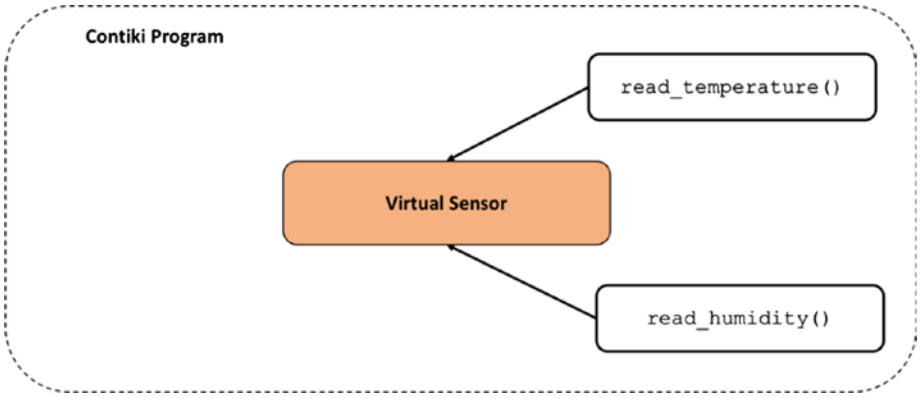


Figure 2-6. *A simple library for virtual sensor*

Now, we can start to develop. Create a project folder called `demo-sensor`. Then, create files as follows:

- `mysensor.h` is a header file that declares `read_temperature()` and `read_humidity()` functions.
- `mysensor.c` implements `read_temperature()` and `read_humidity()` functions.
- `demo-sensor.c` is the main program that uses `mysensor` library.
- `Makefile` is used for compiler parameters.

This project structure is shown in Figure 2-7.

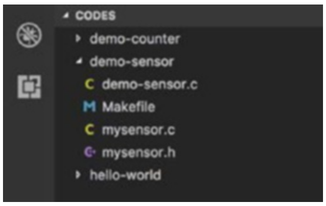


Figure 2-7. *Project structure for demo-sensor*

Now, we implement all files, starting with `mysensor.h`. It's a header file that exposes two functions:

```
// mysensor.h
#ifndef MYSENSOR_H
#define MYSENSOR_H

struct Sensor {
    char  name[15];
    float value;
 };
```

```
struct Sensor read_temperature();
struct Sensor read_humidity();

#endif
```

These sensor functions will be used as a general sensor that is implemented for temperature and humidity in the `mysensor.c` file. The following is the complete code for `mysensor.c`:

```
// mysensor.c
#include "mysensor.h"
#include <string.h>
#include <stdlib.h>

float random_value(float min, float max)
{
    float scale = rand() / (float) RAND_MAX;
    return min + scale * (max - min);
}
struct Sensor read_temperature()
{
    struct Sensor temp;

    strncpy(temp.name, "Temperature", 15);
    temp.value = random_value(0, 35);

    return temp;
}
struct Sensor read_humidity()
{
    struct Sensor humdidty;

    strncpy(humdidty.name, "Humidity", 15);
    humdidty.value = random_value(40, 80);

    return humdidty;
}
```

We generate a random number for our functions. Moreover, we use the Sensor library in our main program, demo-sensor.c. We use an event timer for the reading period. The following is the complete code for demo-sensor.c:

```
// demo-sensor.c
#include "contiki.h"
#include "sys/etimer.h"
#include "mysensor.h"
#include <stdio.h>

PROCESS(sensor_process, "Sensor process");
AUTOSTART_PROCESSES(&sensor_process);

static struct etimer timer;


PROCESS_THREAD(sensor_process, ev, data)
{
  PROCESS_BEGIN();

  printf("Demo Virtual Sensor\n");
  while(1) {
    etimer_set(&timer, 3 * CLOCK_SECOND);
    PROCESS_WAIT_EVENT_UNTIL(etimer_expired(&timer));

    struct Sensor temp = read_temperature();
    printf("%s: %.2f\n", temp.name, temp.value);
    struct Sensor hum = read_humidity();
    printf("%s: %.2f\n", hum.name, hum.value);
    printf("------------\n");
  }

  PROCESS_END();
}
```

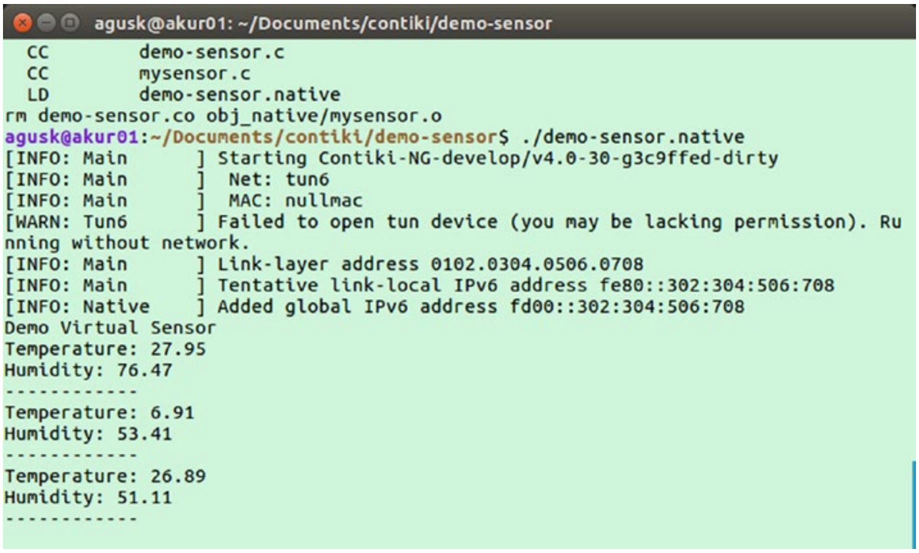
Last, we create a Makefile for compiler parameters. We set PROJECT_SOURCEFILES with mysensor.c. Change the CONTIKI value to your Contiki root folder. The following is the content of the Makefile:

```
CONTIKI_PROJECT = demo-sensor
all: $(CONTIKI_PROJECT)

PROJECT_SOURCEFILES += mysensor.c


CONTIKI = /home/user/Documents/book/contiki
include $(CONTIKI)/Makefile.include
```

Now, we can compile and upload the program into the WSN mote. We can compile and run it for targeting native. Open Terminal and navigate to the project folder. Then, type these commands:

```
$ make TARGET=native
$ ./demo-sensor.native
```

This program will display sensor values after the event timer is raised. You can see my program output in Figure 2-8.



```
  CC        demo-sensor.c
  CC        mysensor.c
  LD        demo-sensor.native
rm demo-sensor.co obj_native/mysensor.o
agusk@akur01:~/Documents/contiki/demo-sensor$ ./demo-sensor.native
[INFO: Main      ] Starting Contiki-NG-develop/v4.0-30-g3c9ffed-dirty
[INFO: Main      ]  Net: tun6
[INFO: Main      ]  MAC: nullmac
[WARN: Tun6      ] Failed to open tun device (you may be lacking permission). Ru
nning without network.
[INFO: Main      ] Link-layer address 0102.0304.0506.0708
[INFO: Main      ] Tentative link-local IPv6 address fe80::302:304:506:708
[INFO: Native    ] Added global IPv6 address fd00::302:304:506:708
Demo Virtual Sensor
Temperature: 27.95
Humidity: 76.47
------------
Temperature: 6.91
Humidity: 53.41
------------
Temperature: 26.89
Humidity: 51.11
------------
```

Figure 2-8. *Program output for demo-sensor application*

Summary

We have explored the Contiki-NG basic programming language. This is a core language based on the C programming language that will help you to develop a Contiki-NG application. We built a Contiki-NG application that utilized a header library and event timer with Contiki-NG program features.

In the next chapter, we will learn how to work with concurrency in Contiki-NG programs in order to deal with multiple jobs.

CHAPTER 3

Concurrency

Multi-tasking can increase the scalability of your Contiki-NG applications. This chapter will explore how to work with concurrency in Contiki-NG applications.

The following is a list of topics that will be covered in this chapter:

- Introduction to concurrency
- Concurrency approach in Contiki-NG
- Threading
- Task scheduling

Introduction to Concurrency

Concurrency is the ability to perform more than one task at the same time. Let's say you have a WSN mote with multiple sensor devices. You want to sense through all the sensors at the same time.

We illustrate a concurrency in Figure 3-1. A process can handle multiple tasks with different problem models. We can achieve concurrency by applying a queue that is either FIFO (First In First Out) or LIFO (Last In First Out). Another solution is to apply asynchronous code in our program.

In this chapter, we will explore how to implement concurrency in Contiki-NG applications. Some samples are provided to show how to do it.

A. Kurniawan, *Practical Contiki-NG*, https://doi.org/10.1007/978-1-4842-3408-2_3

Concurrency Approach in Contiki-NG

Contiki-NG provides concurrency features. We can use several approaches to develop application-based concurrency. There are four methods with which we can implement concurrency in Contiki-NG applications, as follows:

- Processes
- Timers
- Threading
- Task scheduling

We will discuss and implement these methods in the next section.

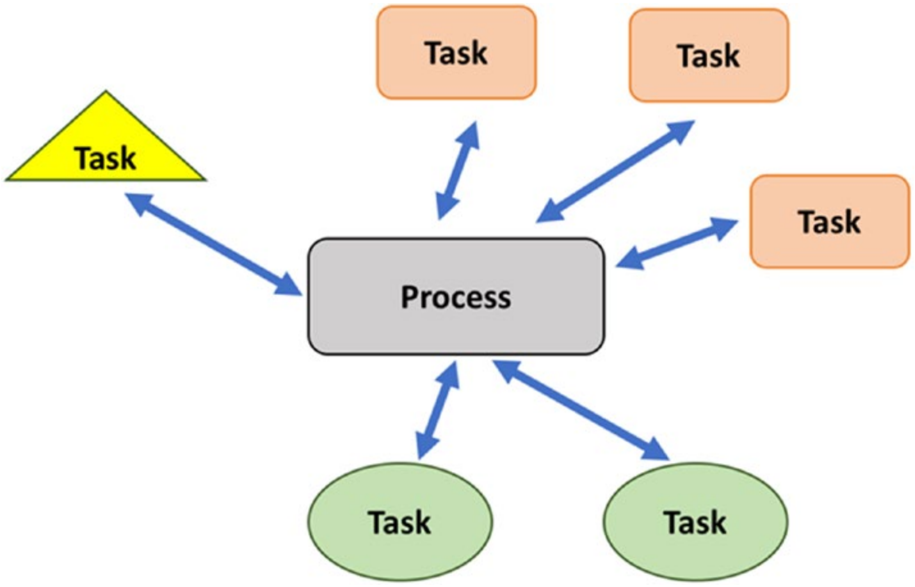


Figure 3-1. *A process performs some tasks*

Introducing Contiki-NG Processes

Contiki-NG applications can run on a process that executes in either cooperative or preemptive mode. Cooperative mode is regular execution in the microcontroller. A process with preemptive mode runs with interruptions resulting from I/O or timers.

In general, we can create a process in Contiki-NG by calling `PROCESS()`. We can define a process as

```
PROCESS(name, process_name);
```

where

- `name` is a variable of the process, and
- `process_name` is a process name that is represented as a string.

Then, we implement this process using `PROCESS_THREAD`. We can declare this as follows:

```
PROCESS_THREAD(name, ev, data)
{
  PROCESS_BEGIN();
  // do semothing
  PROCESS_END();
}
```

The following is a list of macros APIs for processes:

- `PROCESS_BEGIN()`: Declares the beginning of a process protothread
- `PROCESS_END()`: Declares the end of a process protothread
- `PROCESS_EXIT()`: Exits the process

- `PROCESS_WAIT_EVENT()`: Waits for any event
- `PROCESS_WAIT_EVENT_UNTIL()`: Waits for an event, but with conditions
- `PROCESS_YIELD()`: Waits for any event; equivalent to `PROCESS_WAIT_EVENT()`
- `PROCESS_WAIT_UNTIL()`: Waits for a given condition; may not yield the microcontroller
- `PROCESS_PAUSE()`: Temporarily yields the microcontroller

For demo purposes, we will create a simple Contiki-NG app. Create a folder called `demo-process`. Then, create two files, `demo-process.c` and `Makefile`. The first step is to write a program for `demo-process.c`. We define three processes as follows:

```
#include "contiki.h"
#include <stdio.h>

PROCESS(myprocess1, "process 1");
PROCESS(myprocess2, "process 2");
PROCESS(myprocess3, "process 3");
AUTOSTART_PROCESSES(&myprocess1,&myprocess2,&myprocess3);
```

You can see that we created three processes. We pass these process variables to `AUTOSTART_PROCESSES()`. We implement the following code for our processes:

```
PROCESS_THREAD(myprocess1, ev, data)
{
  PROCESS_BEGIN();

  printf("This message from process 1\n");
  PROCESS_END();
}
PROCESS_THREAD(myprocess2, ev, data)
{
  PROCESS_BEGIN();

  printf("This message from process 2\n");

  PROCESS_END();
}
PROCESS_THREAD(myprocess3, ev, data)
{
  PROCESS_BEGIN();

  printf("This message from process 3\n");

  PROCESS_END();
}
```

Save this program. We continue to Makefile. We declare our program and the path of the Contiki-NG root directory via CONTIKI:

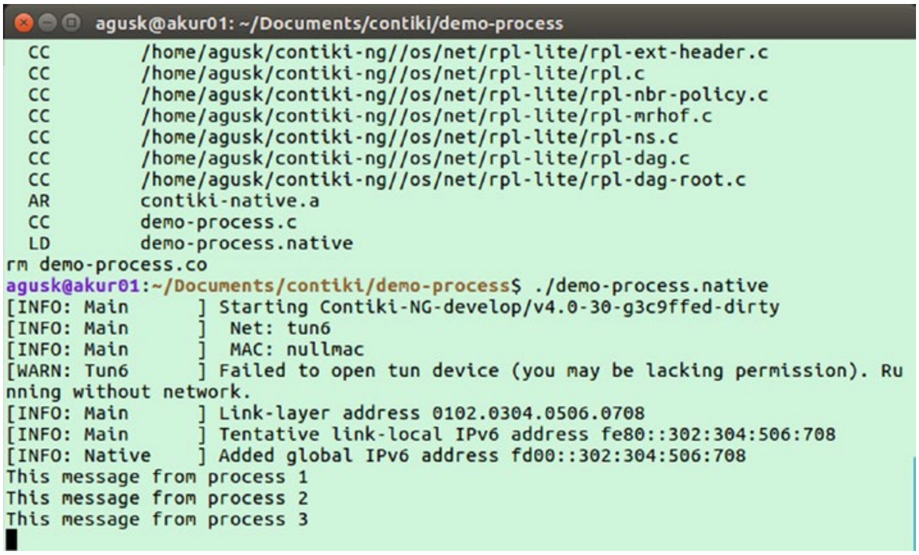
```
CONTIKI_PROJECT = demo-process
all: $(CONTIKI_PROJECT)

CONTIKI = /home/user/Documents/book/contiki
include $(CONTIKI)/Makefile.include
```

Change the Contiki-NG path directory in CONTIKI.

To compile and run the program, you can open Terminal and navigate to a program folder. You can type the following commands. For instance, we run on local native OS:

```
$ make TARGET=native
$ ./demo-process.native
```

If this succeeds, you will see messages from each process in Terminal. See Figure 3-2.



```
agusk@akur01: ~/Documents/contiki/demo-process
  CC        /home/agusk/contiki-ng//os/net/rpl-lite/rpl-ext-header.c
  CC        /home/agusk/contiki-ng//os/net/rpl-lite/rpl.c
  CC        /home/agusk/contiki-ng//os/net/rpl-lite/rpl-nbr-policy.c
  CC        /home/agusk/contiki-ng//os/net/rpl-lite/rpl-mrhof.c
  CC        /home/agusk/contiki-ng//os/net/rpl-lite/rpl-ns.c
  CC        /home/agusk/contiki-ng//os/net/rpl-lite/rpl-dag.c
  CC        /home/agusk/contiki-ng//os/net/rpl-lite/rpl-dag-root.c
  AR        contiki-native.a
  CC        demo-process.c
  LD        demo-process.native
rm demo-process.co
agusk@akur01:~/Documents/contiki/demo-process$ ./demo-process.native
[INFO: Main      ] Starting Contiki-NG-develop/v4.0-30-g3c9ffed-dirty
[INFO: Main      ]  Net: tun6
[INFO: Main      ]  MAC: nullmac
[WARN: Tun6      ] Failed to open tun device (you may be lacking permission). Ru
nning without network.
[INFO: Main      ] Link-layer address 0102.0304.0506.0708
[INFO: Main      ] Tentative link-local IPv6 address fe80::302:304:506:708
[INFO: Native    ] Added global IPv6 address fd00::302:304:506:708
This message from process 1
This message from process 2
This message from process 3
```

Figure 3-2. *Running demo-process app*

Working with Timers

We can perform some activities by utilizing timer objects. Contiki-NG has one clock and several timer modules, such as `timer`, `stimer`, `ctimer`, `etimer`, and `rtimer`. All these libraries can be found in the `<contiki>/os/sys` folder.

We will explore these libraries in the next section.

Clock Library

The `Clock` library can be used for doing general activities with time. It is declared in `clock.h` from the `<contiki>/os/sys` folder. You can see the content of the `clock.h` file here:

```
clock_time_t clock_time(); // Get the system time.
unsigned long clock_seconds(); // Get the system time in
seconds.
void clock_delay(unsigned int delay); // Delay the CPU.
void clock_wait(int delay); // Delay the CPU for a number of
clock ticks.
void clock_init(void); // Initialize the clock module.
CLOCK_SECOND; // The number of ticks per second.
```

To use this library, call these functions directly from the program. For instance, you can access a clock time by calling the `clock_time()` function:

```
  clock_time_t t = clock_time();
  printf("Timer start: %lu \n", t);
```

Timer Library

The `Timer` library provides functions for setting, resetting, and restarting timers, and for checking if a timer has expired. This library is found in the `timer.h` file and defines several functions as follows:

```
void timer_set(struct timer *t, clock_time_t interval);
// Start the timer.
void timer_reset(struct timer *t); // Restart the timer from
the previous expiration time.
void timer_restart(struct timer *t); // Restart the timer from
current time.
int timer_expired(struct timer *t); // Check if the timer has
expired.
clock_time_t timer_remaining(struct timer *t); // Get the time
until the timer expires.
```

An application must manually check if its timers have expired. To use the Timer library, we call `timer_set()`. Then, we can verify an expired timer by calling the `timer_expired()` function:

```
timer_set(&timer_timer, 3 * CLOCK_SECOND);

if(timer_expired(&timer_timer)){
  t = clock_time();
  printf("timer expired: %lu \n", t);
}
```

Stimer Library

The `Stimer` library is similar to the `timer` library, but uses time values in seconds. The following is a list of `Stimer` functions defined in the `stimer.h` file.

```
void stimer_set(struct stimer *t, unsigned long interval);
// Start the timer.
void stimer_reset(struct stimer *t); // Restart the stimer from
the previous expiration time.
void stimer_restart(struct stimer *t); // Restart the stimer
from current time.
int stimer_expired(struct stimer *t); // Check if the stimer
has expired.
unsigned long stimer_remaining(struct stimer *t); // Get the
time until the timer expires.
```

We can use the `Stimer` library with the same approach as the `timer` library. We set a time by calling `stimer_set()`. Then, we check for an expired timer using the `stimer_expired()` function:

```
    stimer_set(&stimer_timer, 3);

    if(stimer_expired(&stimer_timer)){
      t = clock_time();
      printf("stimer expired: %lu \n", t);
    }
```

Etimer Library

The Etimer library is an event timer library that generates an event. We can verify this event using PROCESS_WAIT_EVENT_UNTIL(). You can see event timer declarations in the etimer.h file:

```
void etimer_set(struct etimer *t, clock_time_t interval);
// Start the timer.
void etimer_reset(struct etimer *t); // Restart the timer from
the previous expiration time.
void etimer_restart(struct etimer *t); // Restart the timer
from current time.
void etimer_stop(struct etimer *t); // Stop the timer.
int etimer_expired(struct etimer *t); // Check if the timer has
expired.
int etimer_pending(); // Check if there are any non-expired
event timers.
clock_time_t etimer_next_expiration_time(); // Get the next
event timer expiration time.
void etimer_request_poll(); // Inform the etimer library that
the system clock has changed.
```

For demo purposes, we can call `etimer_set()` to set our event timer. Then, we wait for the expired event using `PROCESS_WAIT_EVENT_UNTIL()`:

```
etimer_set(&etimer_timer, 3 * CLOCK_SECOND);

while(1){

  PROCESS_WAIT_EVENT_UNTIL(etimer_expired(&etimer_timer));
  etimer_reset(&etimer_timer);

}
```

CTimer Library

The `CTimer` library provides a function callback that will be called when timer expiration occurs. `CTimer` functions are defined in the `ctimer.h` file:

```
void ctimer_set(struct ctimer *c, clock_time_t t, void(*f)(void *),
void *ptr); // Start the timer.
void ctimer_reset(struct ctimer *t); // Restart the timer from
the previous expiration time.
void ctimer_restart(struct ctimer *t); // Restart the timer
from current time.
void ctimer_stop(struct ctimer *t); // Stop the timer.
int ctimer_expired(struct ctimer *t); // Check if the timer has
expired.
```

For this demo, we can define a function, `perform_ctime_function()`. This function is passed to `ctimer_set()` when we set the `ctimer` library:

```
void
perform_ctime_callback()
{
  printf("Process demo_timer3: ctimer callback called\n");

}
```

```
ctimer_set(&ctimer_timer, CLOCK_SECOND, perform_ctime_callback,
NULL);
```

Rtimer Library

The Rtimer library provides scheduling and execution for real-time tasks. We can define a specific execution time when we set rtimer using the rtimer_set() function. You can see the rtimer function in the rtimer.h file:

```
RTIMER_CLOCK_LT(a, b); // This should give TRUE if 'a' is less
than 'b', otherwise false.
RTIMER_ARCH_SECOND; // The number of ticks per second.
void rtimer_arch_init(void); // Initialize the rtimer
architecture code.
rtimer_clock_t rtimer_arch_now(); // Get the current time.
int rtimer_arch_schedule(rtimer_clock_t wakeup_time);
//  Schedule a call to rtimer_run_next().
```

For implementation, we declare a function that is passed in the rtimer_set() function. We also set the execution time:

```
static rtimer_clock_t timeout_rtimer = RTIMER_SECOND / 2;
void
perform_rtime_callback()
{
  printf("Process demo_timer3: rtimer callback called\n");

}

rtimer_set(&rtimer_timer, RTIMER_NOW() + timeout_rtimer, 0,
perform_rtime_callback, NULL);
```

Put It All Together

Now, we will try to use Contiki-NG to run a demo about timers. We create a folder, called demo-timer. We create two files, demo-timer.c and Makefile. We put all code from all the timer libraries in the demo-timer.c file.

The following is the complete code for the demo-timer.c file:

```
#include "contiki.h"
#include "sys/clock.h"
#include "sys/timer.h"
#include "sys/stimer.h"
#include "sys/etimer.h"
#include "sys/ctimer.h"
#include "sys/rtimer.h"
#include <stdio.h>

static int counter;
static struct timer timer_timer;
static struct stimer stimer_timer;
static struct etimer etimer_timer;
static struct ctimer ctimer_timer;
static struct rtimer rtimer_timer;

PROCESS(demo_timer1, "demo timer stimer");
PROCESS(demo_timer2, "demo etimer");
PROCESS(demo_timer3, "demo ctime");
PROCESS(demo_timer4, "demo rtime");
AUTOSTART_PROCESSES(&demo_timer1, &demo_timer2,
  &demo_timer3, &demo_timer4);

static rtimer_clock_t timeout_rtimer = RTIMER_SECOND / 2;


void
perform_ctime_callback()
```

```
{
  printf("Process demo_timer3: ctimer callback called\n");

  if(counter>=2){
    printf("ctimer is stopped\n");
    ctimer_stop(&ctimer_timer);
  }
  else
    ctimer_reset(&ctimer_timer);

}


void
perform_rtime_callback()
{
  printf("Process demo_timer3: rtimer callback called\n");

  if(counter<2){
    rtimer_set(&rtimer_timer, RTIMER_NOW() + timeout_rtimer, 0,
      perform_rtime_callback, NULL);
  }
  else
    printf("rtimer is stopped\n");
}

PROCESS_THREAD(demo_timer1, ev, data)
{
  PROCESS_BEGIN();
  counter = 0;
  clock_time_t t = clock_time();
  printf("Timer start: %lu \n", t);

  timer_set(&timer_timer, 3 * CLOCK_SECOND);
  stimer_set(&stimer_timer, 3);
  while(1){

    if(timer_expired(&timer_timer)){
      t = clock_time();
      printf("timer expired: %lu \n", t);
      timer_reset(&timer_timer);
      counter++;
    }
    if(stimer_expired(&stimer_timer)){
      t = clock_time();
      printf("stimer expired: %lu \n", t);
      stimer_reset(&stimer_timer);
      counter++;
    }
    if(counter>=2)
      break;
  }
  printf("demo_timer1 process end\n");
  PROCESS_END();
}

PROCESS_THREAD(demo_timer2, ev, data)
{
  PROCESS_BEGIN();

  printf("demo etimer\n");
  clock_time_t t = clock_time();
  printf("etimer start: %lu \n", t);

  printf("set etimer 3 clock_second\n");
  etimer_set(&etimer_timer, 3 * CLOCK_SECOND);

  while(1){

    PROCESS_WAIT_EVENT_UNTIL(etimer_expired(&etimer_timer));
    etimer_reset(&etimer_timer);
    if(counter>=2)
      break;
  }
  printf("demo_timer2 process end\n");

  PROCESS_END();
}
PROCESS_THREAD(demo_timer3, ev, data)
{
  PROCESS_BEGIN();

  printf("demo ctime\n");
  while(1) {
    ctimer_set(&ctimer_timer, CLOCK_SECOND, perform_ctime_
    callback, NULL);
    PROCESS_YIELD();
  }

  PROCESS_END();
}

PROCESS_THREAD(demo_timer4, ev, data)
{
  PROCESS_BEGIN();

  printf("demo rtime\n");
  while(1) {
    rtimer_set(&rtimer_timer, RTIMER_NOW() + timeout_rtimer, 0,
      perform_rtime_callback, NULL);

    PROCESS_YIELD();
  }

  PROCESS_END();
}
```

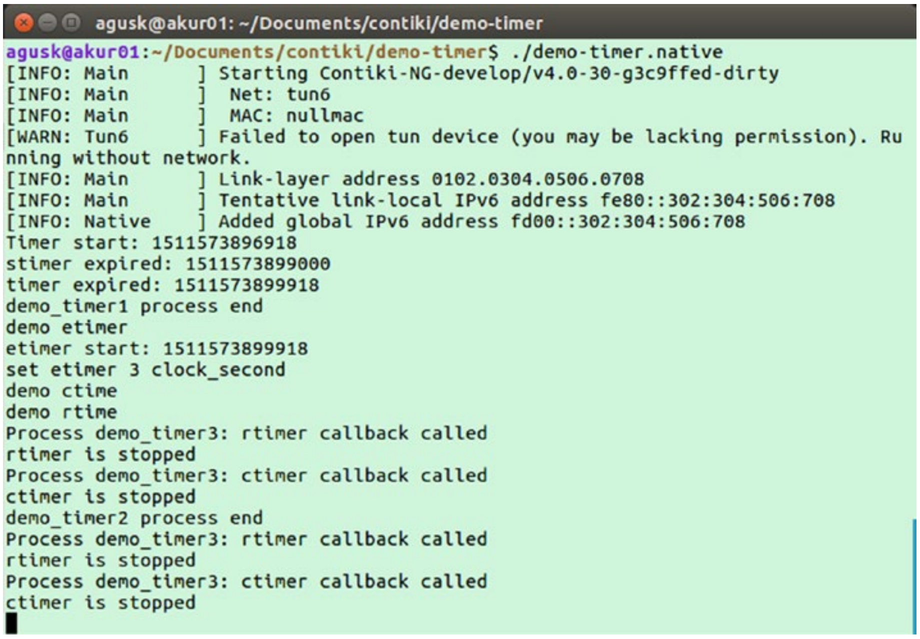
Next, we write the `Makefile` file with the following code:

```
CONTIKI_PROJECT = demo-timer
all: $(CONTIKI_PROJECT)

CONTIKI = /home/user/Documents/book/contiki
include $(CONTIKI)/Makefile.include
```

Change `CONTIKI` to your Contiki-NG root folder. Now, you can compile and run this program. Open Terminal and navigate to your program folder. Then, type these commands:

```
$ make TARGET=native
$ ./demo-timer.native
```

This program will run in Terminal. You can run it on your Contiki-NG hardware. You can see the program output on Terminal in Figure 3-3.



```
agusk@akur01:~/Documents/contiki/demo-timer$ ./demo-timer.native
[INFO: Main      ] Starting Contiki-NG-develop/v4.0-30-g3c9ffed-dirty
[INFO: Main      ]  Net: tun6
[INFO: Main      ]  MAC: nullmac
[WARN: Tun6      ] Failed to open tun device (you may be lacking permission). Ru
nning without network.
[INFO: Main      ] Link-layer address 0102.0304.0506.0708
[INFO: Main      ] Tentative link-local IPv6 address fe80::302:304:506:708
[INFO: Native    ] Added global IPv6 address fd00::302:304:506:708
Timer start: 1511573896918
stimer expired: 1511573899000
timer expired: 1511573899918
demo_timer1 process end
demo etimer
etimer start: 1511573899918
set etimer 3 clock_second
demo ctime
demo rtime
Process demo_timer3: rtimer callback called
rtimer is stopped
Process demo_timer3: ctimer callback called
ctimer is stopped
demo_timer2 process end
Process demo_timer3: rtimer callback called
rtimer is stopped
Process demo_timer3: ctimer callback called
ctimer is stopped
```

Figure 3-3. *Running demo-timer app*

Threading

Contiki-NG OS removes multithreading from the source code. You can read about it at `https://github.com/contiki-ng/contiki-ng/pull/172`. This probably is also supported in the next version. If you want to work with multithreading, you can use regular Contiki. Contiki provides threading so that we can perform many tasks through `mt_thread` in the `mt.h` header file. This file is found in the Contiki source code in the `<contiki_root>/core/sys/` folder. You can see several functions in the `mt.h` file as follows:

```
void mt_init(void) : Initializes the library.
void mt_remove(void) : Uninstalls the library.
void mt_start(struct mt_thread *thread, void (* function)(void *),
void *data) : Starts a thread.
void mt_exit(void) : Exits a thread.
void mt_exec(struct mt_thread *thread) : Execute as thread.
void mt_yield(void) : Release control voluntarily.
void mt_stop(struct mt_thread *thread) : Stops a thread.
```

In this section, we will develop multithreading using Contiki. Please skip this section if you still work with Contiki-NG.

You can see threading states for a Contiki app in Figure 3-4.

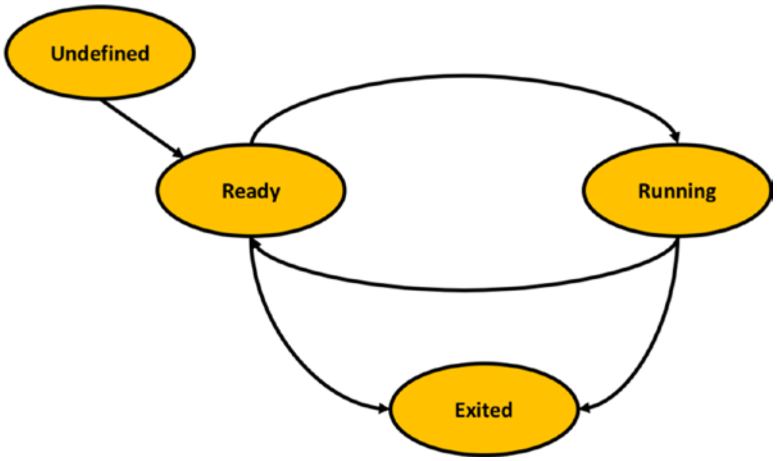


***Figure 3-4.** Threading states for a Contiki app*

Each thread runs on a process. Each thread can communicate by either sharing resources or exchanging data. Figure 3-5 shows three threads running on a process.

We can create a thread within a Contiki process with the following method:

```
static struct mt_thread thread1;
int n1=10;
mt_init();
mt_start(&thread1, thread_compute, &n1);
```

Our thread is passed a function, called `thread_compute`. We also give a parameter for our function. The `thread_compute()` function can be declared as follows:

```
void
thread_compute(void *data)
{
  printf("calling thread_compute()\n");
```

```
    // do something
    mt_yield();
    mt_exit();
}
```

You can see that our function is executed and then that thread is closed using `mt_yield()` and `mt_exit()`.

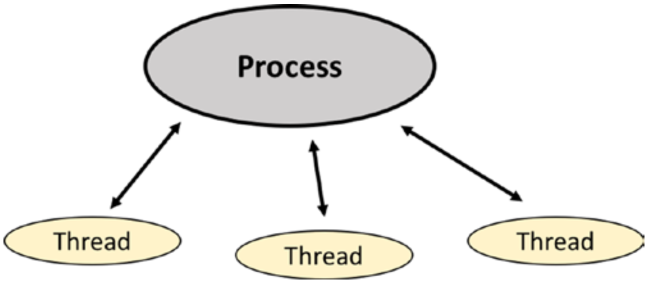


Figure 3-5. *Threads in Contiki process*

For demo purposes, we create two threads. Each thread will execute a loop for a certain time based on the input data. You can start by creating a folder, called `demo-thread`. Then, create two files, `demo-thread.c` and `Makefile`.

First, we write code in the `demo-thread.c` file. We define two threads. We also create a function, called `thread_compute()`, that will be passed on our threads.

You can write the following complete code for the `demo-thread.c` file:

```
#include "contiki.h"
#include "sys/mt.h"
#include <stdio.h>

PROCESS(mythread, "demo thread");
AUTOSTART_PROCESSES(&mythread);
```

```
static int count;

void
thread_compute(void *data)
{
  printf("calling thread_compute()\n");

  int num = *((int*)data);
  printf("num: %d\n", num);
  int i;

  int val = 0;
  for(i=0;i<num;i++){
    val+=2;

  }
  printf("num: %d, total: %d\n", num, val);
  count++;
  mt_yield();
  mt_exit();

}

PROCESS_THREAD(mythread, ev, data)
{
  PROCESS_BEGIN();
  printf("demo threading\n");

  static struct mt_thread thread1;
  static struct mt_thread thread2;

  int n1=10, n2=20;

  mt_init();
  mt_start(&thread1, thread_compute, &n1);
  mt_start(&thread2, thread_compute, &n2);
  mt_exec(&thread1);
  mt_exec(&thread2);
  while(1) {

    if(count>1) {
      mt_stop(&thread1);
      mt_stop(&thread2);

      break;
    }

  }


  printf("thread exit\n");
  mt_remove();

  PROCESS_END();
}
```

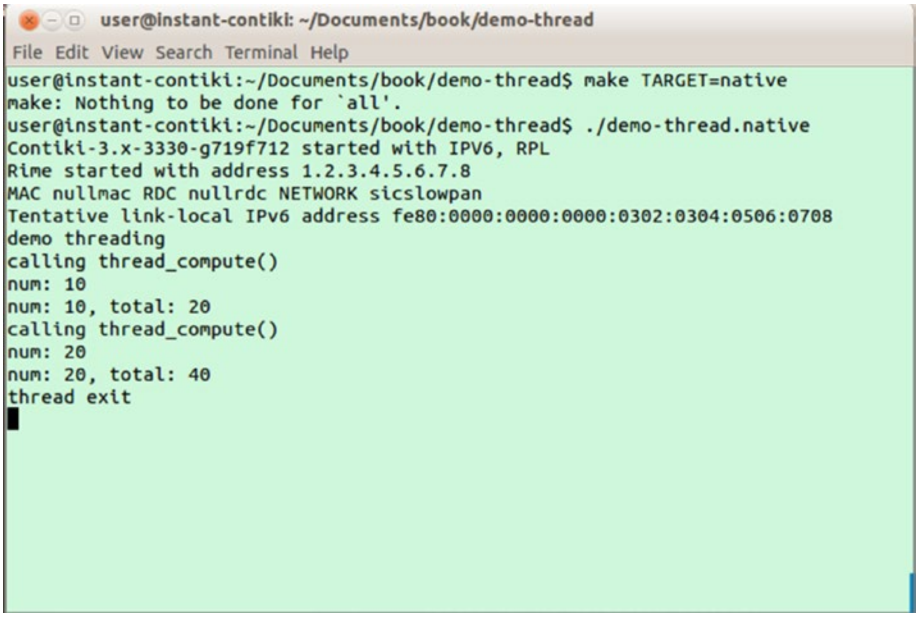
Now, we can create the `Makefile`. We declare the project name and Contiki path, which is defined ion `CONTIKI`:

```
CONTIKI_PROJECT = demo-thread
all: $(CONTIKI_PROJECT)

CONTIKI_WITH_RIME = 1
CONTIKI = /home/user/Documents/book/contiki
include $(CONTIKI)/Makefile.include
```

You can save all the files. You can compile and run the program with these commands in Terminal:

```
$ make TARGET=native
$ ./demo-thread.native
```

A sample of the program output can be seen in Figure 3-6.


user@instant-contiki: ~/Documents/book/demo-thread
File Edit View Search Terminal Help

```
user@instant-contiki:~/Documents/book/demo-thread$ make TARGET=native
make: Nothing to be done for `all'.
user@instant-contiki:~/Documents/book/demo-thread$ ./demo-thread.native
Contiki-3.x-3330-g719f712 started with IPV6, RPL
Rime started with address 1.2.3.4.5.6.7.8
MAC nullmac RDC nullrdc NETWORK sicslowpan
Tentative link-local IPv6 address fe80:0000:0000:0000:0302:0304:0506:0708
demo threading
calling thread_compute()
num: 10
num: 10, total: 20
calling thread_compute()
num: 20
num: 20, total: 40
thread exit
```

Figure 3-6. *Program output for demo-thread*

Task Scheduling

Task scheduling means that all tasks are scheduled to be executed. In a Contiki-NG application, task scheduling collects all tasks in process, timers, and threading.

In this section, we will try to implement task scheduling by utilizing the `Etimer` library. Our task list will be stored on the Contiki-NG list that you can find in the `<contiki>/os/lib/list.h` file. Figure 3-7 shows our demo to implement task scheduling.

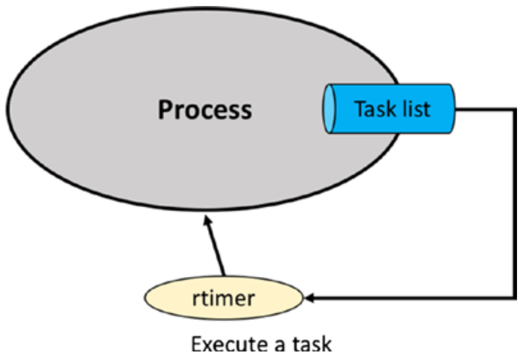


Figure 3-7. *Executing tasks*

Now, create a folder, called `demo-scheduling`. We also create a `demo-scheduling.c` file for our main program. The following is a complete program for the `demo-scheduling.c` file:

```
#include "contiki.h"
#include "sys/clock.h"
#include "sys/rtimer.h"
#include "lib/list.h"
#include <stdio.h>

PROCESS(demo_taskscheduling, "demo task scheduling");
AUTOSTART_PROCESSES(&demo_taskscheduling);

static struct rtimer rtimer_timer;

struct simple_task {
  struct simple_task *next;
  int value;
};

static struct simple_task *s;
static int number_task = 10;
static int is_completed = -1;
```

```
LIST(task_list);

void
perform_rtime_callback(struct rtimer *t, void *ptr)
{
  printf("task callback called\n");

  int num = *((int*)ptr);
  printf("perform task=%d\n", num);

  s = list_item_next(s);
  if(s!=NULL){
    rtimer_set(&rtimer_timer, RTIMER_NOW() + (RTIMER_SECOND/2), 1,
    perform_rtime_callback,&s->value);
  }else{
    printf("all tasks completed\n");
    is_completed = 1;
  }
}

PROCESS_THREAD(demo_taskscheduling, ev, data)
{
  PROCESS_BEGIN();

  printf("demo task schedule\n");

  list_init(task_list);
  int i;

  printf("prepare task data\n");
  struct simple_task task[10];
  for(i=0;i<number_task;i++){
    task[i].value = i + 1;
    list_add(task_list, &task[i]);
  }
  s = list_head(task_list);
  rtimer_set(&rtimer_timer, RTIMER_NOW() + (RTIMER_SECOND/2), 1,
    perform_rtime_callback,&s->value);

  while(1) {
    if(is_completed>0)
      break;
  }
  printf("program exit\n");
  PROCESS_END();
}
```

To compile and run the program, you should create a `Makefile` file with the compiler configuration. We can create these scripts:

```
CONTIKI_PROJECT = demo-scheduling
all: $(CONTIKI_PROJECT)

CONTIKI = /home/user/Documents/book/contiki
include $(CONTIKI)/Makefile.include
```

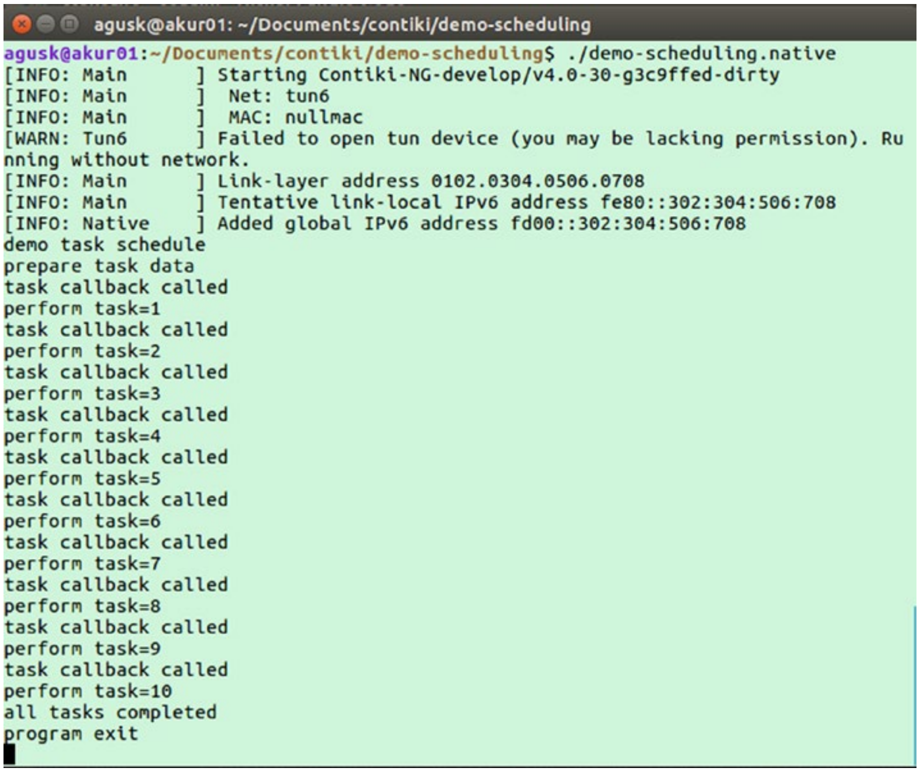
Change `CONTIKI` to your Contiki-NG root path.

Now, you can compile and run this program. For instance, we compile and run it for a local native app. Open a Terminal and type these commands:

```
$ make TARGET=native
$ ./demo-scheduling.native
```

If it succeeds, all tasks will be executed. You can see the program output in Figure 3-8.

How does this work?



```
agusk@akur01: ~/Documents/contiki/demo-scheduling
agusk@akur01:~/Documents/contiki/demo-scheduling$ ./demo-scheduling.native
[INFO: Main      ] Starting Contiki-NG-develop/v4.0-30-g3c9ffed-dirty
[INFO: Main      ]  Net: tun6
[INFO: Main      ]  MAC: nullmac
[WARN: Tun6      ] Failed to open tun device (you may be lacking permission). Ru
nning without network.
[INFO: Main      ] Link-layer address 0102.0304.0506.0708
[INFO: Main      ] Tentative link-local IPv6 address fe80::302:304:506:708
[INFO: Native    ] Added global IPv6 address fd00::302:304:506:708
demo task schedule
prepare task data
task callback called
perform task=1
task callback called
perform task=2
task callback called
perform task=3
task callback called
perform task=4
task callback called
perform task=5
task callback called
perform task=6
task callback called
perform task=7
task callback called
perform task=8
task callback called
perform task=9
task callback called
perform task=10
all tasks completed
program exit
```

Figure 3-8. *Program output for demo-scheduling*

This program starts by declaring a task list in the `struct` model:

```
struct simple_task {
  struct simple_task *next;
  int value;
};

static struct simple_task *s;
static int number_task = 10;
static int is_completed = -1;
LIST(task_list);
```

Then, it generates the task list in the main process:

```
list_init(task_list);
int i;

printf("prepare task data\n");
struct simple_task task[10];
for(i=0;i<number_task;i++){
  task[i].value = i + 1;
  list_add(task_list, &task[i]);
}
```

Next, it runs a task by picking it up from the task list:

```
s = list_head(task_list);
rtimer_set(&rtimer_timer, RTIMER_NOW() + (RTIMER_SECOND/2), 1,
  perform_rtime_callback,&s->value);
```

Each task will be executed in the `perform_rtime_callback()` function. After completion, it gets a task again and then executes it:

```
void
perform_rtime_callback(struct rtimer *t, void *ptr)
{
  printf("task callback called\n");

  int num = *((int*)ptr);
  printf("perform task=%d\n", num);

  s = list_item_next(s);
  if(s!=NULL){
    rtimer_set(&rtimer_timer, RTIMER_NOW() + (RTIMER_SECOND/2), 1,
    perform_rtime_callback,&s->value);
  }else{
    printf("all tasks completed\n");
    is_completed = 1;
  }
}
```

To exit from our program, we can check our program state:

```
while(1) {
  if(is_completed>0)
    break;
}
```

Summary

We have learned how to implement concurrency in Contiki-NG OS. Performing several tasks in the Contiki-NG application has been reviewed. We explored process, timers, threading, and task scheduling.

In the next chapter, we will learn how to communicate between a Contiki-NG application and the computer.

CHAPTER 4

Contiki-NG and Computer Communication

Dada communication capabilities available on WSN motes enable the exchange of data among WSN motes. In this chapter, we will learn how Contiki-NG aids communication among WSN motes and from a WSN mote to a computer. We will also explore how to build middleware that enables WSN motes to communicate with other systems.

The following is a list of topics we will cover in this chapter:

- Communication models for Contiki-NG
- Serial communication
- Building communication among Contiki-NG motes
- Building communication between computer and Contiki-NG motes
- Developing middleware

A. Kurniawan, *Practical Contiki-NG*, https://doi.org/10.1007/978-1-4842-3408-2_4

Communication Models for Contiki-NG

How you want to communicate between WSN motes and computers will determine what kind of communication model you use. As you know, each WSN mote usually has network capability so it can exchange data with WSN motes and computers.

A communication model for Contiki-NG is depicted in Figure 4-1. Some WSN motes have the capability to connect to servers directly, but other motes may not, so those motes use a hub/gateway/middleware to communicate with servers.

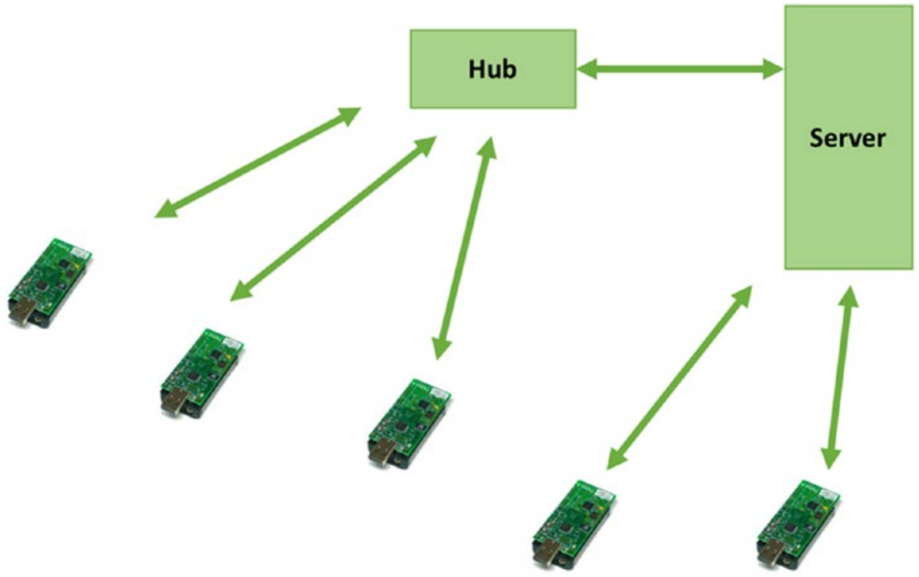


Figure 4-1. *Communication models in Contiki-NG*

In this chapter, we will learn how WSN motes communicate with others. We need at least two motes to implement our demo.

Serial Communication

Serial communication can be defined as a process used to send and receive a bit at a time sequentially. Sometimes serial communication is called UART (Universal Asynchronous Receiver/Transmitter). Technically, we already used serial communication when we uploaded Contiki-NG programs to WSN motes in previous chapters. We also communicate with WSN motes via the `printf()` function. Then, we listen to the messages from `printf()` using the command `make login`.

A serial communication protocol is represented in Figure 4-2. In hardware implementation, a serial communication needs at least three pinouts. These are Rx (Receiver), Tx (Transmitter), and GND (Ground) pins.

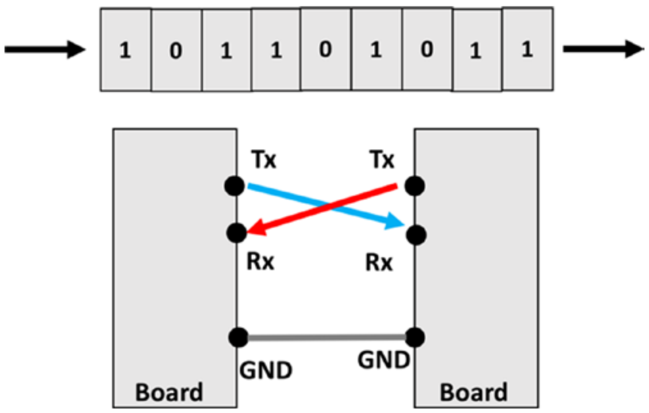


Figure 4-2. *Serial communication*

Communication Between Contiki Mote and Computer

In this section, we will build Contiki and Contiki-NG programs to communicate between a Contiki mote and a computer. This is useful because we can control our Contiki motes from the computer. Running applications on a computer has benefits, such as interacting with the database server and communicating with the cloud server.

There are a lot of methods used to communicate between a computer and a Contiki mote. We will focus on two methods: serial communication and shell. We will explore these methods in the next section.

Let's build!

Access Contiki Motes via Serial Communication

Since our WSN motes are attached to the computer through serial communication, we can initiate communication between the computer and a WSN mote. Some application platforms, such as C/C++, Java, Python, C#, and Node.js, provide libraries with which to implement serial communication.

In this section, we will try to access WSN motes using Python through serial communication. To implement serial communication in Python, we use the `pyserial` library. You can find this library at https://pypi.python.org/pypi/pyserial. This library can be installed using pip.

You can verify if your computer has installed pip or not. You can type this command in Terminal:

```
$ which pip
```

If you don't get a response, it means your computer is missing the pip program. You can install pip using this command in Terminal:

```
$ sudo apt-get install python-pip
```

Now, you can install the `pyserial` library by typing this command in Terminal:

```
$ pip install pyserial
```

You also can install the `pyserial` library using `easy_install`. You can type this command in Terminal:

```
$ easy_install -U pyserial
```

Make sure your computer is connected to the Internet.

Next, you must write a Python program to listen for incoming messages on a specific serial port. You should know which serial port is used by the Contiki mote. You need it because you will use it on your program.

To find a serial port from the Contiki mote, you can open Terminal and type this command:

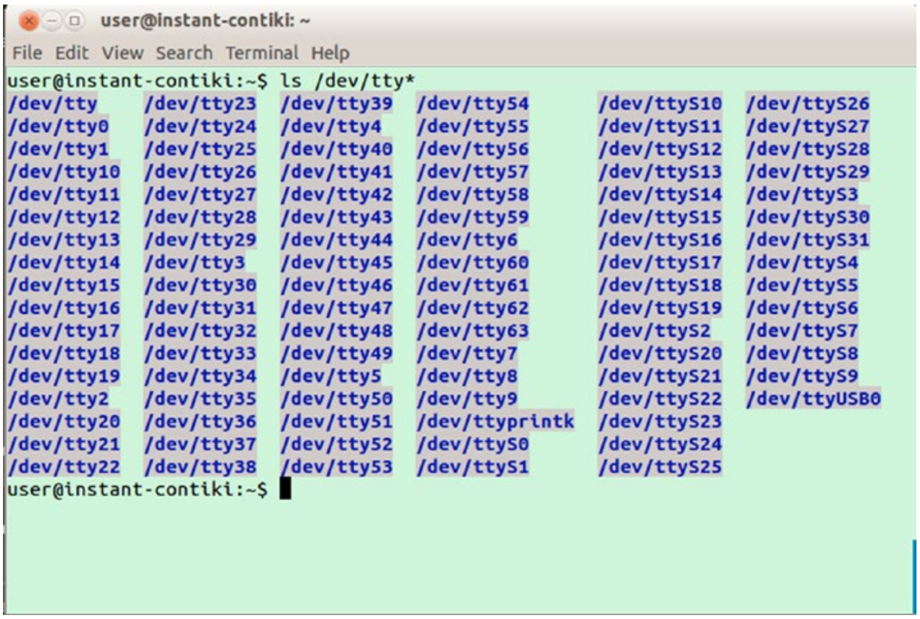
```
$ ls /dev/tty*
```

You should see a list of connected serial ports available on your computer. Depending on your Contiki mote model, you can verify the port by turning the mote on/off so you should which a new attached serial port. For instance, my Contiki mote is detected as `/dev/ttyUSB0.` You can see it in Figure 4-3.

Now, you will develop the Python program. You will print all incoming data from the serial port to the console. Set the baudrate to 115200 for the serial-port speed. Create a file, called `contiki-viewer.py`, and write these complete scripts. Change the `PORT` value to that for your Contiki-NG mote:

```
#!/usr/bin/python
import serial

PORT ='/dev/ttyUSB0'
ser = serial.Serial(
        port=PORT,\
        baudrate=115200,\
        parity=serial.PARITY_NONE,\
        stopbits=serial.STOPBITS_ONE,\
        bytesize=serial.EIGHTBITS,\
        timeout=0)

print("connected to: " + ser.portstr)
ser.write("help\n")
while True:
        line = ser.readline()
        if line:
                print(line),

ser.close()
```

Save this program.



```
user@instant-contiki:~$ ls /dev/tty*
/dev/tty    /dev/tty23  /dev/tty39  /dev/tty54      /dev/ttyS10  /dev/ttyS26
/dev/tty0   /dev/tty24  /dev/tty4   /dev/tty55      /dev/ttyS11  /dev/ttyS27
/dev/tty1   /dev/tty25  /dev/tty40  /dev/tty56      /dev/ttyS12  /dev/ttyS28
/dev/tty10  /dev/tty26  /dev/tty41  /dev/tty57      /dev/ttyS13  /dev/ttyS29
/dev/tty11  /dev/tty27  /dev/tty42  /dev/tty58      /dev/ttyS14  /dev/ttyS3
/dev/tty12  /dev/tty28  /dev/tty43  /dev/tty59      /dev/ttyS15  /dev/ttyS30
/dev/tty13  /dev/tty29  /dev/tty44  /dev/tty6       /dev/ttyS16  /dev/ttyS31
/dev/tty14  /dev/tty3   /dev/tty45  /dev/tty60      /dev/ttyS17  /dev/ttyS4
/dev/tty15  /dev/tty30  /dev/tty46  /dev/tty61      /dev/ttyS18  /dev/ttyS5
/dev/tty16  /dev/tty31  /dev/tty47  /dev/tty62      /dev/ttyS19  /dev/ttyS6
/dev/tty17  /dev/tty32  /dev/tty48  /dev/tty63      /dev/ttyS2   /dev/ttyS7
/dev/tty18  /dev/tty33  /dev/tty49  /dev/tty7       /dev/ttyS20  /dev/ttyS8
/dev/tty19  /dev/tty34  /dev/tty5   /dev/tty8       /dev/ttyS21  /dev/ttyS9
/dev/tty2   /dev/tty35  /dev/tty50  /dev/tty9       /dev/ttyS22  /dev/ttyUSB0
/dev/tty20  /dev/tty36  /dev/tty51  /dev/ttyprintk  /dev/ttyS23
/dev/tty21  /dev/tty37  /dev/tty52  /dev/ttyS0      /dev/ttyS24
/dev/tty22  /dev/tty38  /dev/tty53  /dev/ttyS1      /dev/ttyS25
user@instant-contiki:~$
```

Figure 4-3. *Getting a list of serial ports in your computer*

To simulate this demo, you should upload the Contiki-NG program to a Contiki-NG mote. You can use the same program from Chapter 1, Hello World. You should upload that program into the Contiki mote.

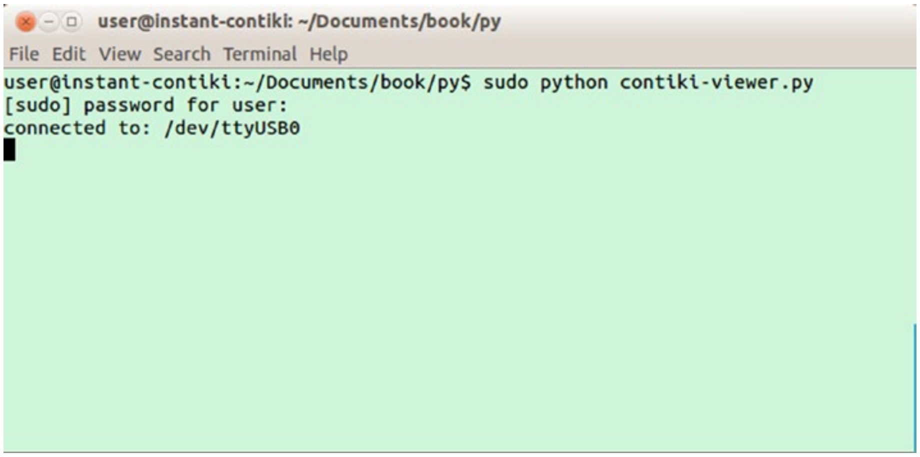
After Contiki-NG is deployed with a Contiki-NG program, you can run the Python program, `contiki-viewer.py`, by typing this command:

```
$ python contiki-viewer.py
```

If you have error issues related to security access, you probably should run it with administrator privileges. Type this command:

```
$ sudo python contiki-viewer.py
```

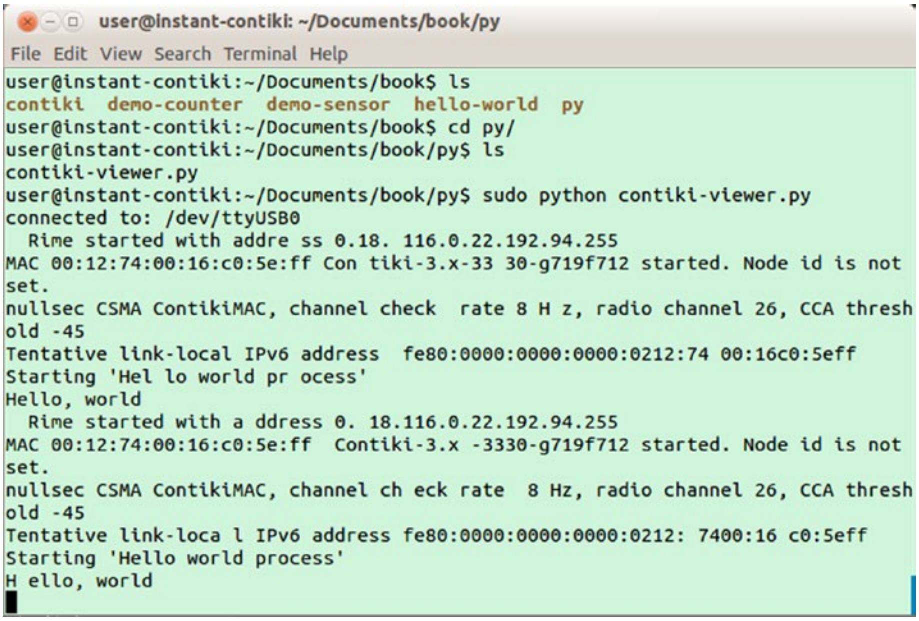
After it has executed, you will see that this program is waiting for incoming messages from the serial port, as shown in Figure 4-4.


user@instant-contiki: ~/Documents/book/py
File Edit View Search Terminal Help

```
user@instant-contiki:~/Documents/book/py$ sudo python contiki-viewer.py
[sudo] password for user:
connected to: /dev/ttyUSB0
```

Figure 4-4. *Executing Python program for listening to the serial port*

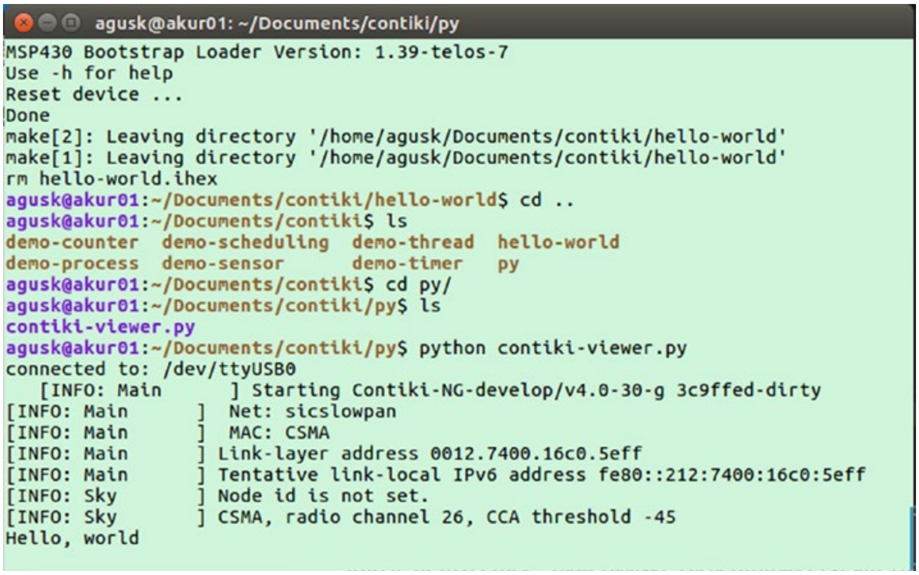
If you do not see anything, you should reset your Contiki mote. Now the message from the Hello World program can be seen on the console. You can see my program depicted in Figure 4-5.


user@instant-contiki: ~/Documents/book/py
File Edit View Search Terminal Help

```
user@instant-contiki:~/Documents/book$ ls
contiki  demo-counter  demo-sensor  hello-world  py
user@instant-contiki:~/Documents/book$ cd py/
user@instant-contiki:~/Documents/book/py$ ls
contiki-viewer.py
user@instant-contiki:~/Documents/book/py$ sudo python contiki-viewer.py
connected to: /dev/ttyUSB0
  Rime started with addre ss 0.18. 116.0.22.192.94.255
MAC 00:12:74:00:16:c0:5e:ff Con tiki-3.x-33 30-g719f712 started. Node id is not
set.
nullsec CSMA ContikiMAC, channel check  rate 8 H z, radio channel 26, CCA thresh
old -45
Tentative link-local IPv6 address  fe80:0000:0000:0000:0212:74 00:16c0:5eff
Starting 'Hel lo world pr ocess'
Hello, world
  Rime started with a ddress 0. 18.116.0.22.192.94.255
MAC 00:12:74:00:16:c0:5e:ff  Contiki-3.x -3330-g719f712 started. Node id is not
set.
nullsec CSMA ContikiMAC, channel ch eck rate  8 Hz, radio channel 26, CCA thresh
old -45
Tentative link-loca l IPv6 address fe80:0000:0000:0000:0212: 7400:16 c0:5eff
Starting 'Hello world process'
H ello, world
```

Figure 4-5. *Reading data from serial port of Contiki using Python*

I have also tested with Contiki-NG on a TelosB mote. It works. You can see that program output in Figure 4-6.



```
agusk@akur01: ~/Documents/contiki/py
MSP430 Bootstrap Loader Version: 1.39-telos-7
Use -h for help
Reset device ...
Done
make[2]: Leaving directory '/home/agusk/Documents/contiki/hello-world'
make[1]: Leaving directory '/home/agusk/Documents/contiki/hello-world'
rm hello-world.ihex
agusk@akur01:~/Documents/contiki/hello-world$ cd ..
agusk@akur01:~/Documents/contiki$ ls
demo-counter  demo-scheduling  demo-thread  hello-world
demo-process  demo-sensor      demo-timer   py
agusk@akur01:~/Documents/contiki$ cd py/
agusk@akur01:~/Documents/contiki/py$ ls
contiki-viewer.py
agusk@akur01:~/Documents/contiki/py$ python contiki-viewer.py
connected to: /dev/ttyUSB0
   [INFO: Main      ] Starting Contiki-NG-develop/v4.0-30-g 3c9ffed-dirty
[INFO: Main      ]  Net: sicslowpan
[INFO: Main      ]  MAC: CSMA
[INFO: Main      ] Link-layer address 0012.7400.16c0.5eff
[INFO: Main      ] Tentative link-local IPv6 address fe80::212:7400:16c0:5eff
[INFO: Sky       ] Node id is not set.
[INFO: Sky       ] CSMA, radio channel 26, CCA threshold -45
Hello, world
```

***Figure 4-6.** Reading data from serial port of Contiki-NG using Python*

How does this work?

This program starts by initializing the `serial` library and activating the serial port of the Contiki-NG mote:

```
import serial

PORT ='/dev/ttyUSB0'
ser = serial.Serial(
        port=PORT,\
        baudrate=115200,\
        parity=serial.PARITY_NONE,\
        stopbits=serial.STOPBITS_ONE,\
        bytesize=serial.EIGHTBITS,\
        timeout=0)
```

]

After the serial port is activated, we listen for incoming message from that serial port. We call `readline()` to read data from the serial port. Once we receive data, we print the data to the console:

```
while True:
      line = ser.readline()
      if line:
              print(line),

ser.close()
```

Last, we close our serial port by calling the `close()` method.

Contiki Shell

Contiki OS provides a shell API that we can utilize to communicate with internal Contiki-NG motes. We find the shell API in the Contiki source code in `<Contiki-root>/apps/shell`. You should see several API objects, shown in Figure 4-7.

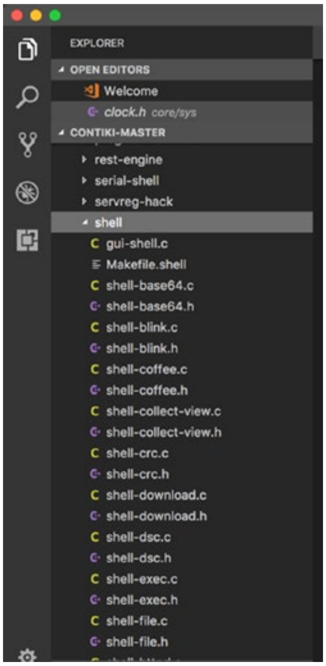
Contiki shell is very useful. Let's say you build and deploy a Contiki application onto a Contiki mote. Then, you want to analyze what is happening inside the Contiki mote. To do this, you can build a custom Contiki shell related to your needs. You call the shell from the Contiki-NG mote and perform your analysis.

One important thing that you should know is the limitations on Contiki mote storage and resources. Building more Contiki shell APIs means using more mote resources. Make sure your Contiki shell is optimal for your Contiki mote model.

In this section, we will learn how to build a Contiki shell application and then deploy it to a Contiki mote. For this simple demo, we will use a Contiki sample from the Contiki source code. You can see it at `<Contiki-root>examples/example-shell`. This program runs for native platforms such as a computer.

Open the example-shell.c file. You should see the PROCESS_THREAD(example_shell_process, ev, data) function, as follows:

```
PROCESS_THREAD(example_shell_process, ev, data)
{
  PROCESS_BEGIN();

  serial_shell_init();

  shell_base64_init();
  shell_blink_init();
  /*shell_coffee_init();*/
  shell_download_init();
  /*shell_exec_init();*/
  shell_file_init();
  shell_httpd_init();
  shell_irc_init();
  /*shell_ping_init();*/ /* uIP ping */
  shell_power_init();
  /*shell_profile_init();*/
  shell_ps_init();
  /*shell_reboot_init();*/
  shell_rime_debug_init();
  shell_rime_netcmd_init();
  shell_rime_ping_init(); /* Rime ping */
  shell_rime_sendcmd_init();
  shell_rime_sniff_init();
  shell_rime_init();
  /*shell_rsh_init();*/
  shell_run_init();
  shell_sendtest_init();
  /*shell_sky_init();*/
  shell_tcpsend_init();
  shell_text_init();
  shell_time_init();
  shell_udpsend_init();
  shell_vars_init();
  shell_wget_init();

  PROCESS_END();
}
```



```
OPEN EDITORS
  Welcome
  clock.h core/sys
CONTIKI-MASTER
  rest-engine
  serial-shell
  servreg-hack
  shell
    gui-shell.c
    Makefile.shell
    shell-base64.c
    shell-base64.h
    shell-blink.c
    shell-blink.h
    shell-coffee.c
    shell-coffee.h
    shell-collect-view.c
    shell-collect-view.h
    shell-crc.c
    shell-crc.h
    shell-download.c
    shell-download.h
    shell-dsc.c
    shell-dsc.h
    shell-exec.c
    shell-exec.h
    shell-file.c
    shell-file.h
```

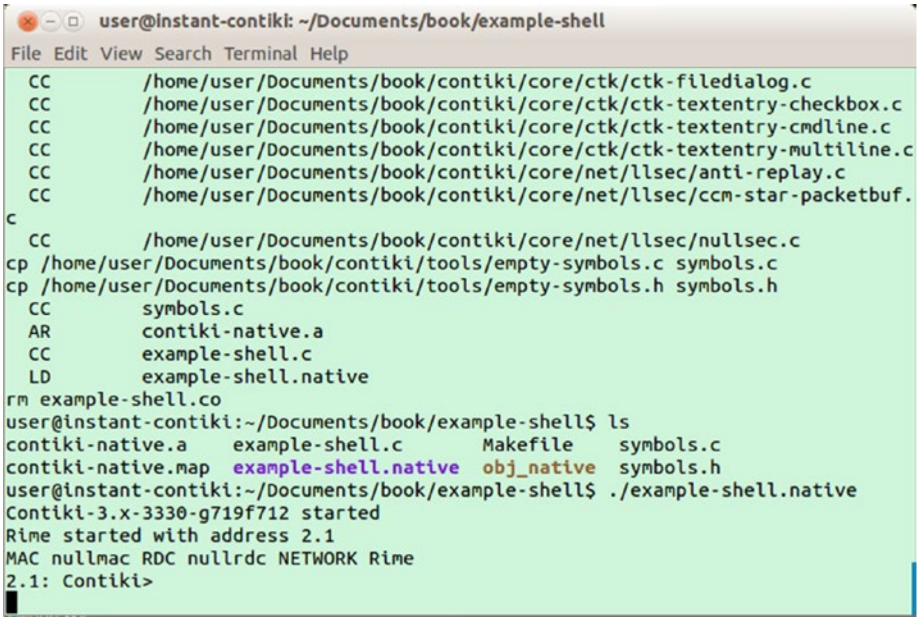
Figure 4-7. *Contiki shell APIs in Contiki source code*

Each shell API is defined as `shell_xxx()`. Remarked codes are not supported for native platforms such as a computer.

Now, you can compile and run this program. Open Terminal and navigate to the `<Contiki-root>examples/example-shell` folder. Then, type these commands:

```
$ make TARGET=native
$ ./example-shell.native
```

If it succeeds, you should see the Contiki shell that is shown in Figure 4-8.



user@instant-contiki: ~/Documents/book/example-shell

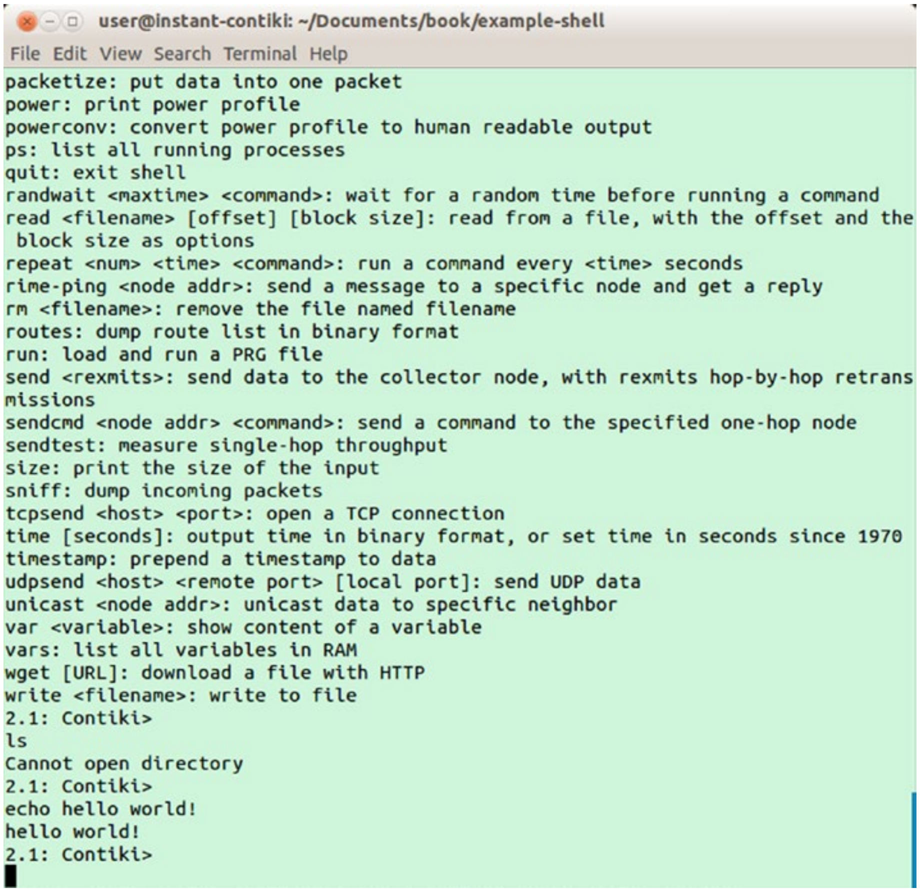
```
  CC        /home/user/Documents/book/contiki/core/ctk/ctk-filedialog.c
  CC        /home/user/Documents/book/contiki/core/ctk/ctk-textentry-checkbox.c
  CC        /home/user/Documents/book/contiki/core/ctk/ctk-textentry-cmdline.c
  CC        /home/user/Documents/book/contiki/core/ctk/ctk-textentry-multiline.c
  CC        /home/user/Documents/book/contiki/core/net/llsec/anti-replay.c
  CC        /home/user/Documents/book/contiki/core/net/llsec/ccm-star-packetbuf.
c
  CC        /home/user/Documents/book/contiki/core/net/llsec/nullsec.c
cp /home/user/Documents/book/contiki/tools/empty-symbols.c symbols.c
cp /home/user/Documents/book/contiki/tools/empty-symbols.h symbols.h
  CC        symbols.c
  AR        contiki-native.a
  CC        example-shell.c
  LD        example-shell.native
rm example-shell.co
user@instant-contiki:~/Documents/book/example-shell$ ls
contiki-native.a    example-shell.c        Makefile    symbols.c
contiki-native.map  example-shell.native  obj_native  symbols.h
user@instant-contiki:~/Documents/book/example-shell$ ./example-shell.native
Contiki-3.x-3330-g719f712 started
Rime started with address 2.1
MAC nullmac RDC nullrdc NETWORK Rime
2.1: Contiki>
```

Figure 4-8. *Executing example-shell application*

For this demo, you call one of the Contiki shells. To get a list of Contiki shells, you can call the `help` shell command:

```
Contiki > help
Contiki > echo hello world!
```

You should get a list of supported shells in the console. Then, execute echo shell command. A sample of the program's output can be seen in Figure 4-9.


user@instant-contiki: ~/Documents/book/example-shell
File Edit View Search Terminal Help

```
packetize: put data into one packet
power: print power profile
powerconv: convert power profile to human readable output
ps: list all running processes
quit: exit shell
randwait <maxtime> <command>: wait for a random time before running a command
read <filename> [offset] [block size]: read from a file, with the offset and the
 block size as options
repeat <num> <time> <command>: run a command every <time> seconds
rime-ping <node addr>: send a message to a specific node and get a reply
rm <filename>: remove the file named filename
routes: dump route list in binary format
run: load and run a PRG file
send <rexmits>: send data to the collector node, with rexmits hop-by-hop retrans
missions
sendcmd <node addr> <command>: send a command to the specified one-hop node
sendtest: measure single-hop throughput
size: print the size of the input
sniff: dump incoming packets
tcpsend <host> <port>: open a TCP connection
time [seconds]: output time in binary format, or set time in seconds since 1970
timestamp: prepend a timestamp to data
udpsend <host> <remote port> [local port]: send UDP data
unicast <node addr>: unicast data to specific neighbor
var <variable>: show content of a variable
vars: list all variables in RAM
wget [URL]: download a file with HTTP
write <filename>: write to file
2.1: Contiki>
ls
Cannot open directory
2.1: Contiki>
echo hello world!
hello world!
2.1: Contiki>
```

***Figure 4-9.** Running shell sample*

You have run a Contiki shell on the computer as a native application. Now, you will build a Contiki shell for a Contiki mote. For demo purposes, I will use TelosB hardware that's type is Sky.

You will use a sample program from the Contiki source code. You can find `shell-sky` at `<Contiki-root>examples/shell-sky folder`.

If you open the sky-shell.c file, you should see the PROCESS_THREAD(sky_shell_process, ev, data) code as follows:

```
PROCESS_THREAD(sky_shell_process, ev, data)
{
  PROCESS_BEGIN();

#if WITH_PERIODIC_DEBUG
  ctimer_set(&debug_timer, 20 * CLOCK_SECOND, periodic_debug, NULL);
#endif /* WITH_PERIODIC_DEBUG */

  serial_shell_init();
  shell_blink_init();
  /*  shell_file_init();
      shell_coffee_init();*/
  /*  shell_download_init();*/
  shell_rime_sendcmd_init();
  /*  shell_ps_init();*/
  shell_reboot_init();
  shell_rime_init();
  shell_rime_netcmd_init();
  /*  shell_rime_ping_init();
  shell_rime_debug_init();
  shell_rime_debug_runicast_init();*/
  /*  shell_rime_sniff_init();*/
  shell_sky_init();
  shell_power_init();
  shell_powertrace_init();
  /*  shell_base64_init();*/
  shell_text_init();
  shell_time_init();
  /*  shell_sendtest_init();*/

  shell_collect_view_init();
#if DEBUG_SNIFFERS
  rime_sniffer_add(&s);
#endif /* DEBUG_SNIFFERS */

  PROCESS_END();
}
```

You only use some essential shells due to the Contiki mote's resource limitation. Other shell APIs are remarked.

Now, compile and upload this program into your Contiki mote. For instance, I use the Contiki-NG mote–based Sky. Open Terminal and navigate to the `<Contiki-root>examples/shell-sky` folder. You can type these commands to compile and upload the program to the Contiki-NG mote with `sky` as target:

```
$ make TARGET=sky
$ make TARGET=sky savetarget
$ make shell-sky.upload
```

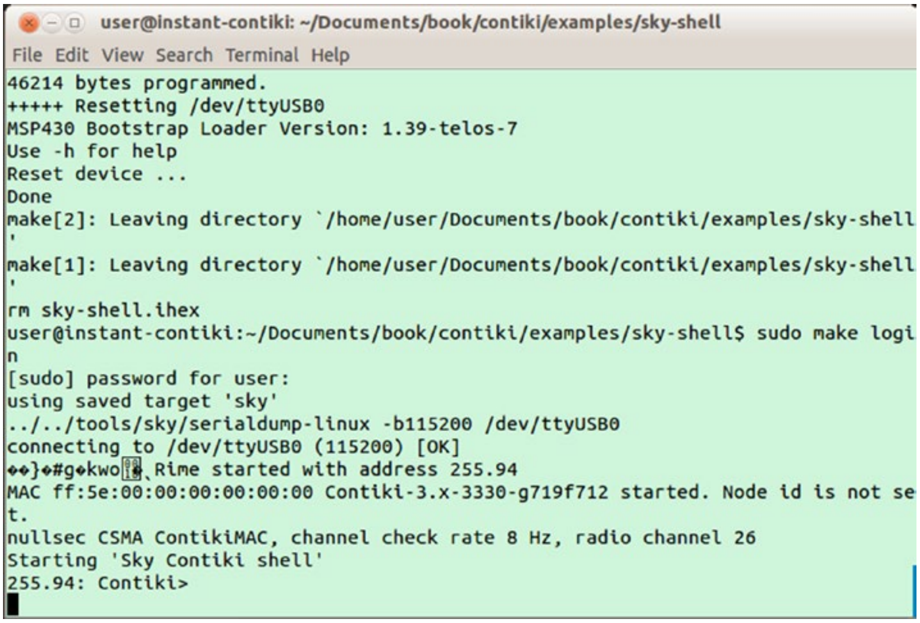
After it has completed, you can monitor your Contiki mote. You can type this command:

```
$ make login
```

Then, reset your Contiki mote in order to use the Contiki shell. If it succeeds, you should see the Contiki shell terminal as follows:

```
$ ./example-shell.native
Contiki-3.x-3330-g719f712 started
Rime started with address 2.1
MAC nullmac RDC nullrdc NETWORK Rime
2.1: Contiki>
```

You can see a sample of the Contiki shell in Figure 4-10.


user@instant-contiki: ~/Documents/book/contiki/examples/sky-shell
File Edit View Search Terminal Help

```
46214 bytes programmed.
+++++ Resetting /dev/ttyUSB0
MSP430 Bootstrap Loader Version: 1.39-telos-7
Use -h for help
Reset device ...
Done
make[2]: Leaving directory `/home/user/Documents/book/contiki/examples/sky-shell
'
make[1]: Leaving directory `/home/user/Documents/book/contiki/examples/sky-shell
'
rm sky-shell.ihex
user@instant-contiki:~/Documents/book/contiki/examples/sky-shell$ sudo make logi
n
[sudo] password for user:
using saved target 'sky'
../../tools/sky/serialdump-linux -b115200 /dev/ttyUSB0
connecting to /dev/ttyUSB0 (115200) [OK]
��}�#g�kwo Rime started with address 255.94
MAC ff:5e:00:00:00:00:00:00 Contiki-3.x-3330-g719f712 started. Node id is not se
t.
nullsec CSMA ContikiMAC, channel check rate 8 Hz, radio channel 26
Starting 'Sky Contiki shell'
255.94: Contiki>
```

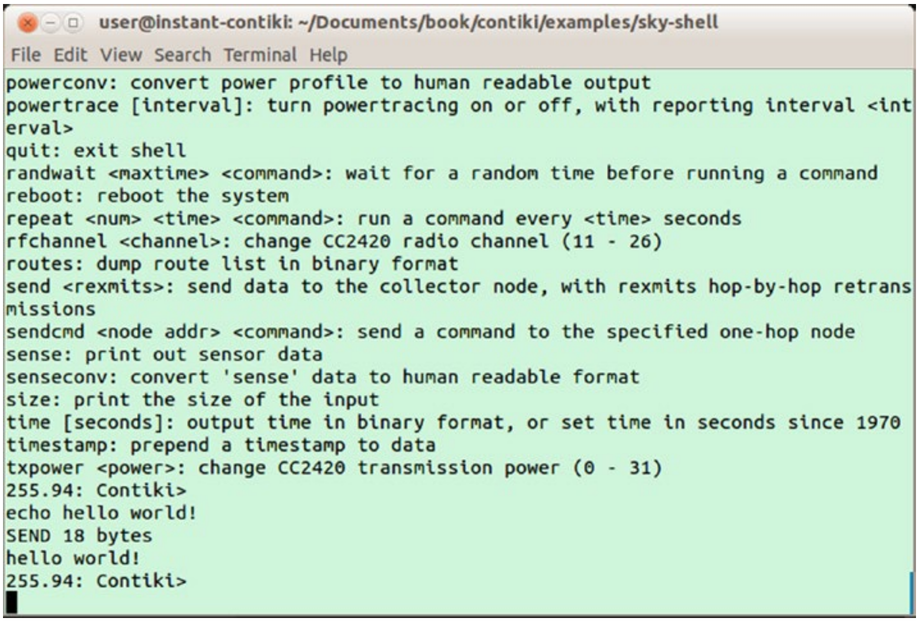
Figure 4-10. *Running Contiki shell on Contiki-NG mote*

From the Contiki shell, you can test it using the commands `help` and `echo`. You can type these commands:

```
Contiki> help
Contiki> echo hello world!
```

A sample of the program output from the Contiki shell can be seen in Figure 4-11.

If you want to exit from the Contiki shell, you can type `exit`. If you get problems quitting from the Contiki shell, you can press CTRL+C to enforce the exit.


user@instant-contiki: ~/Documents/book/contiki/examples/sky-shell
File Edit View Search Terminal Help

```
powerconv: convert power profile to human readable output
powertrace [interval]: turn powertracing on or off, with reporting interval <int
erval>
quit: exit shell
randwait <maxtime> <command>: wait for a random time before running a command
reboot: reboot the system
repeat <num> <time> <command>: run a command every <time> seconds
rfchannel <channel>: change CC2420 radio channel (11 - 26)
routes: dump route list in binary format
send <rexmits>: send data to the collector node, with rexmits hop-by-hop retrans
missions
sendcmd <node addr> <command>: send a command to the specified one-hop node
sense: print out sensor data
senseconv: convert 'sense' data to human readable format
size: print the size of the input
time [seconds]: output time in binary format, or set time in seconds since 1970
timestamp: prepend a timestamp to data
txpower <power>: change CC2420 transmission power (0 - 31)
255.94: Contiki>
echo hello world!
SEND 18 bytes
hello world!
255.94: Contiki>
```

Figure 4-11. *Running shell sample on Contiki mote*

Contiki-NG Shell

Contiki-NG has modified Contiki shell. Contiki-NG shell is defined into a module. You should enable a shell module if you want to use it. The shell structure can be found in the `<Contiki-NG-root>/os/services/shell` folder. You can see it in Figure 4-12.

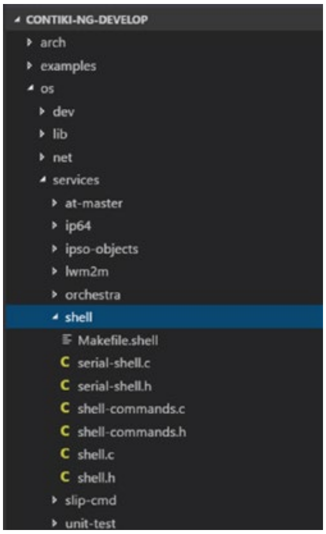


Figure 4-12. *Code structure of Contiki-NG shell*

You can enable the shell module in the `Makefile` file from your projects. Put this script in to enable this module:

```
MODULES += os/services/shell
```

Then, you can compile and upload your project program into your Contiki mote. Since Contiki-NG needs more space on the Contiki mote, your mote probably does not fit the program, so you will get an error while compiling and flashing the program.

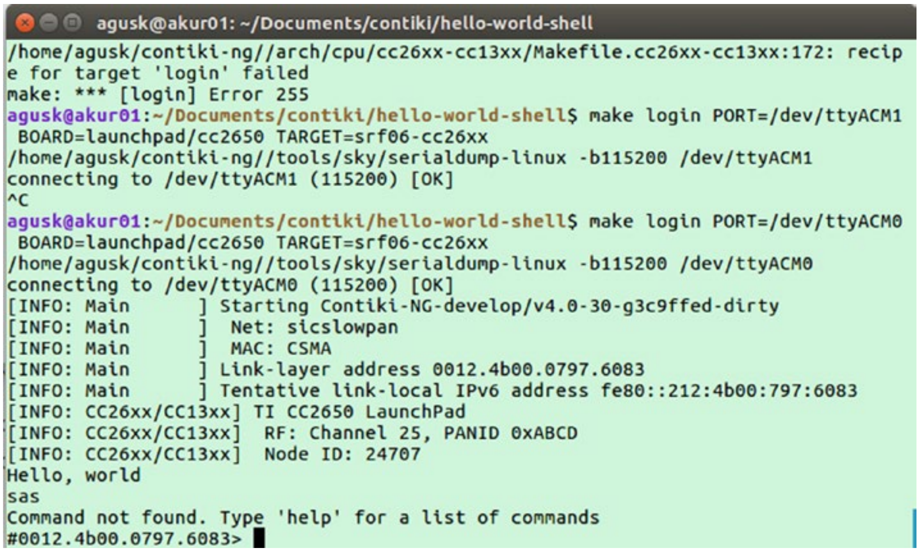
After you succeed in uploading program, you can test it by connecting to the Contiki mote via a serial tool. You should get “>” on the serial Terminal. Not all Contiki motes can run the Contiki-NG shell due to ROM space size. My TelosB board cannot work with this shell. So, I tested it with the TI CC2650 LaunchPad board. It works. I then run this command to access the Contiki-NG serial:

```
$ make login PORT=/dev/ttyACM0 BOARD=launchpad/cc2650
TARGET=srf06-cc26xx
```

If you do not see ">," try to reset the board. Then, press Enter. The program output can be seen in Figure 4-13.

Now, you can test Contiki-NG with several commands. Try to execute these shell commands:

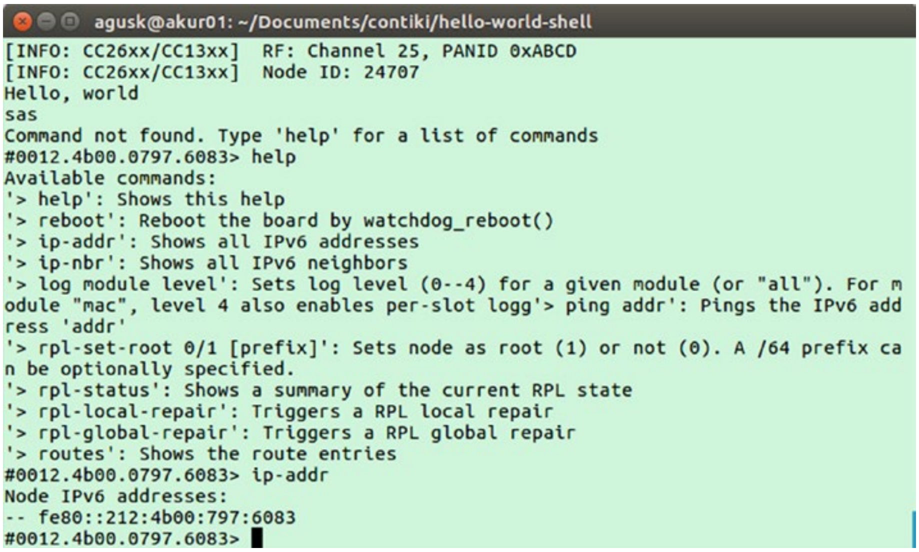
```
> help
> ip-addr
```



```
agusk@akur01: ~/Documents/contiki/hello-world-shell
/home/agusk/contiki-ng//arch/cpu/cc26xx-cc13xx/Makefile.cc26xx-cc13xx:172: recip
e for target 'login' failed
make: *** [login] Error 255
agusk@akur01:~/Documents/contiki/hello-world-shell$ make login PORT=/dev/ttyACM1
 BOARD=launchpad/cc2650 TARGET=srf06-cc26xx
/home/agusk/contiki-ng//tools/sky/serialdump-linux -b115200 /dev/ttyACM1
connecting to /dev/ttyACM1 (115200) [OK]
^C
agusk@akur01:~/Documents/contiki/hello-world-shell$ make login PORT=/dev/ttyACM0
 BOARD=launchpad/cc2650 TARGET=srf06-cc26xx
/home/agusk/contiki-ng//tools/sky/serialdump-linux -b115200 /dev/ttyACM0
connecting to /dev/ttyACM0 (115200) [OK]
[INFO: Main      ] Starting Contiki-NG-develop/v4.0-30-g3c9ffed-dirty
[INFO: Main      ]  Net: sicslowpan
[INFO: Main      ]  MAC: CSMA
[INFO: Main      ] Link-layer address 0012.4b00.0797.6083
[INFO: Main      ] Tentative link-local IPv6 address fe80::212:4b00:797:6083
[INFO: CC26xx/CC13xx] TI CC2650 LaunchPad
[INFO: CC26xx/CC13xx]  RF: Channel 25, PANID 0xABCD
[INFO: CC26xx/CC13xx]  Node ID: 24707
Hello, world
sas
Command not found. Type 'help' for a list of commands
#0012.4b00.0797.6083>
```

Figure 4-13. *Running Contiki-NG shell on TI CC2650 LaunchPad board*

These commands will list all registered Contiki-NG shells and display current IP address. You can see my program output in Figure 4-14.



```
[INFO: CC26xx/CC13xx]  RF: Channel 25, PANID 0xABCD
[INFO: CC26xx/CC13xx]  Node ID: 24707
Hello, world
sas
Command not found. Type 'help' for a list of commands
#0012.4b00.0797.6083> help
Available commands:
'> help': Shows this help
'> reboot': Reboot the board by watchdog_reboot()
'> ip-addr': Shows all IPv6 addresses
'> ip-nbr': Shows all IPv6 neighbors
'> log module level': Sets log level (0--4) for a given module (or "all"). For m
odule "mac", level 4 also enables per-slot logg'> ping addr': Pings the IPv6 add
ress 'addr'
'> rpl-set-root 0/1 [prefix]': Sets node as root (1) or not (0). A /64 prefix ca
n be optionally specified.
'> rpl-status': Shows a summary of the current RPL state
'> rpl-local-repair': Triggers a RPL local repair
'> rpl-global-repair': Triggers a RPL global repair
'> routes': Shows the route entries
#0012.4b00.0797.6083> ip-addr
Node IPv6 addresses:
-- fe80::212:4b00:797:6083
#0012.4b00.0797.6083>
```

Figure 4-14. *Sample of executing Contiki-NG shell*

Customizing Contiki Shell

In some cases you may need to customize the Contiki shell to fit your problems. The thing that you should be aware of is your space and resource usage while implementing a Contiki shell.

In this section, we will learn how to customize a Contiki shell on both Contiki and Contiki-NG. In Contiki-NG, a Contiki shell is called an NG shell. Each customizing shell topic will be explored in the next sections.

Custom Contiki Shell

In the previous section, we learned how to access Contiki and Contiki shells. Now, we will build our own Contiki shell API. For this simple demo, we will develop a Contiki shell with an addition math operation. This API will receive two number parameters. These number parameters will be added and then sent back as the Contiki shell output.

To build our own Contiki shell, we can add our shell objects to the `<Contiki-root>/apps/shell` folder. For our scenario, we add two files, `shell-math.c` and `shell-math.h`. You can see them in Figure 4-15.

There are two steps to building a custom Contiki shell. First, we create an object file (`*.c`) in which to declare all Contiki shell implementations. We declare the Contiki shell API using `SHELL_COMMAND()`. Then, we implement the shell API on a process by declaring it in `PROCESS()`.

Last, we register and initialize our Contiki shell API by calling the `shell_register_command()` function. This function will be called on the `shell_math_init()` function. The Contiki program that will use this shell should call `shell_math_init()` function to access the shell API.

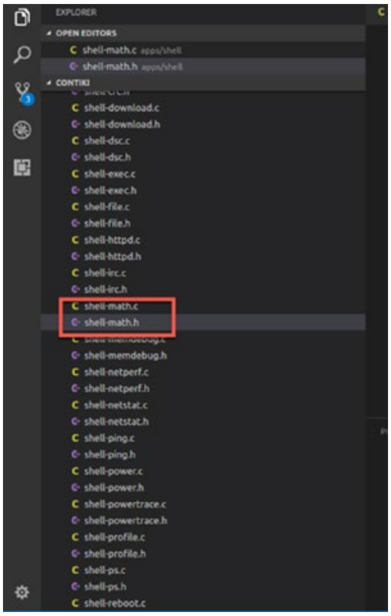


Figure 4-15. *Adding an additional Contiki shell API*

For implementation, we start to write the program in the shell-math.c file. We receive two number input parameters. Then, we perform the addition operation. The following is the complete program for the shell-math.c file:

```
#include "contiki.h"
#include "shell.h"
#include <ctype.h>
#include <stdio.h>
#include <string.h>

/*---------------------------------------------------------------*/
PROCESS(shell_math_process, "math");
SHELL_COMMAND(math_command,
              "math",
              "math: math number1 number2",
              &shell_math_process);
/*---------------------------------------------------------------*/
PROCESS_THREAD(shell_math_process, ev, data)
{
  char *numbers;
  int n1 = 0;
  int n2 = 0;
  char buf[32];

  PROCESS_BEGIN();


  numbers = data;
  if(numbers == NULL || strlen(numbers) == 0) {
    shell_output_str(&math_command,
                 "math number1 number2: number must be given", "");
    PROCESS_EXIT();
  }
  char * pch;
  pch = strtok (numbers," ");
  if (pch != NULL)
  {
      n1 = atoi(pch);
      pch = strtok (NULL, " ");
      if (pch != NULL)
      {
          n2 = atoi(pch);
      }else
      {
        shell_output_str(&math_command,
          "math number1 number2: number must be given", "");
      PROCESS_EXIT();
      }
  }else
  {
    shell_output_str(&math_command,
      "math number1 number2: number must be given", "");
    PROCESS_EXIT();
  }
  int s = n1 + n2;
  sprintf(buf, "%d + %d= %d", n1, n2, s);

  shell_output_str(&math_command, buf, "");

  PROCESS_END();
}
/*---------------------------------------------------------------*/
void
shell_math_init(void)
```

```
{
  shell_register_command(&math_command);
}
/*---------------------------------------------------------------------------*/
```

Input data from the user can be obtained from the data variables in the function parameters. We parse the data into two number variables.

Next, we write a header file, called `shell-math.h`, for our Contiki shell API. We only declare our function, `shell_math_init()`. The following is the complete program for the `shell-math.h` file:

```
#ifndef __SHELL_MATH_H__
#define __SHELL_MATH_H__

#include "shell.h"

void shell_math_init(void);

#endif
```

Save all the files.

Now, we should configure `Makefile` to include these files in compilation. You can open `Makefile.shell` in the same folder with the shell API files. Open this file and add your shell files. You can see them in the codes here:

```
...

shell_src = shell.c shell-reboot.c shell-vars.c shell-ps.c \
            shell-blink.c shell-text.c shell-time.c \
            shell-file.c shell-run.c \
            shell-coffee.c \
            shell-power.c \
            shell-base64.c \
            shell-memdebug.c \
            shell-math.c \
            shell-powertrace.c shell-crc.c
shell_dsc = shell-dsc.c

...
```

Our Contiki shell API is now ready for compiling.

The next step is to develop a Contiki application to use our Contiki shell API, math shell. We create a folder, called `shell-math-demo`. Then, we create two files:

- shell-math-demo.c
- Makefile

The `shell-math-demo.c` file consists of a program to use the Contiki math shell API. The following is the complete program in the `shell-math-demo.c` file:

```
#include "contiki.h"
#include "shell.h"
#include "serial-shell.h"
#include "collect-view.h"

/*---------------------------------------------------------------*/
PROCESS(sky_shell_process, "Sky Contiki shell");
AUTOSTART_PROCESSES(&sky_shell_process);
/*---------------------------------------------------------------*/
#define WITH_PERIODIC_DEBUG 0
#if WITH_PERIODIC_DEBUG
static struct ctimer debug_timer;
static void
periodic_debug(void *ptr)
{
  ctimer_set(&debug_timer, 20 * CLOCK_SECOND, periodic_debug, NULL);
  collect_print_stats();
}
#endif /* WITH_PERIODIC_DEBUG */
/*---------------------------------------------------------------*/
PROCESS_THREAD(sky_shell_process, ev, data)
{
  PROCESS_BEGIN();

#if WITH_PERIODIC_DEBUG
  ctimer_set(&debug_timer, 20 * CLOCK_SECOND, periodic_debug, NULL);
#endif /* WITH_PERIODIC_DEBUG */

  serial_shell_init();
  shell_blink_init();
  shell_reboot_init();
  shell_sky_init();
  shell_power_init();
  shell_powertrace_init();
  shell_text_init();
  shell_time_init();

  shell_collect_view_init();
  shell_math_init();

  PROCESS_END();
}
/*---------------------------------------------------------------*/
```

Furthermore, we write scripts in the `Makefile`. We include Contiki and the project path. You write these complete scripts as follows:

```
CONTIKI_PROJECT = shell-math-demo
all: $(CONTIKI_PROJECT)

APPS = serial-shell powertrace collect-view
CONTIKI = ../..

CONTIKI_WITH_RIME = 1
include $(CONTIKI)/Makefile.include
```

`CONTIKI_WITH_RIME = 1` is used to enable the RIME protocol since Contiki shell uses it on some shell commands. We also supply a testing configuration by including this Makefile, `/home/user/nes/testbed-scripts/Makefile.include`, because some shell commands need it.

Save all files.

Now, we compile our program, `shell-math-demo`. Open Terminal and navigate to the `shell-math-demo` folder. Type these commands:

```
$ make TARGET=sky
$ make shell-math-demo.sky.upload TARGET=sky
```

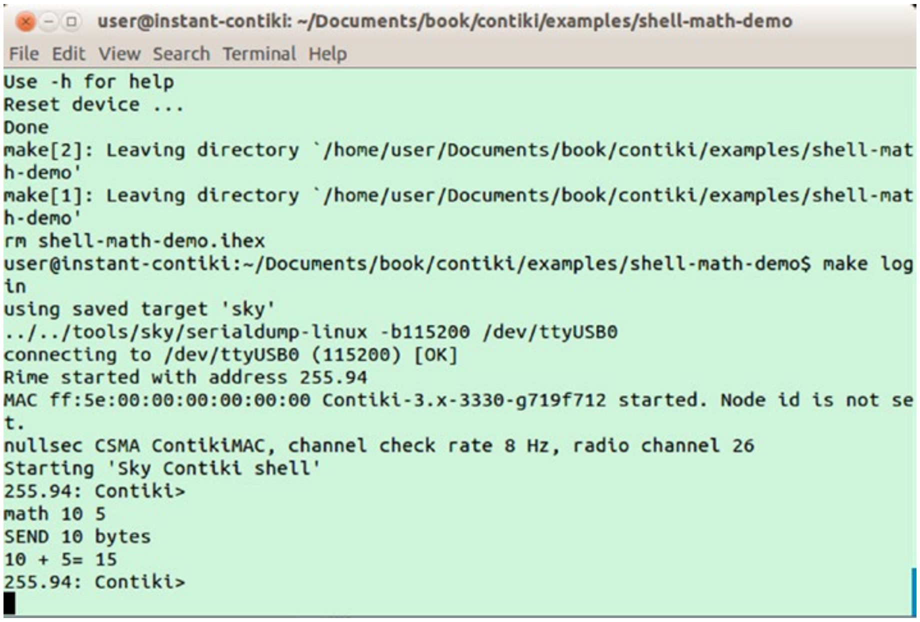
After our program is uploaded to Contiki mote, we can monitor the mote. You can type this command:

```
$ make login
```

If it succeeds, you should see the Contiki shell. Now, we can call our Contiki shell API. We can type this command in the Contiki shell:

```
Contiki> math 10 5
```

This shell will call our Contiki shell API. Value inputs 10 and 5 will be executed to perform the addition operation. You can see a sample of the program output in Figure 4-16.


user@instant-contiki: ~/Documents/book/contiki/examples/shell-math-demo
File Edit View Search Terminal Help

```
Use -h for help
Reset device ...
Done
make[2]: Leaving directory `/home/user/Documents/book/contiki/examples/shell-mat
h-demo'
make[1]: Leaving directory `/home/user/Documents/book/contiki/examples/shell-mat
h-demo'
rm shell-math-demo.ihex
user@instant-contiki:~/Documents/book/contiki/examples/shell-math-demo$ make log
in
using saved target 'sky'
../../tools/sky/serialdump-linux -b115200 /dev/ttyUSB0
connecting to /dev/ttyUSB0 (115200) [OK]
Rime started with address 255.94
MAC ff:5e:00:00:00:00:00:00 Contiki-3.x-3330-g719f712 started. Node id is not se
t.
nullsec CSMA ContikiMAC, channel check rate 8 Hz, radio channel 26
Starting 'Sky Contiki shell'
255.94: Contiki>
math 10 5
SEND 10 bytes
10 + 5= 15
255.94: Contiki>
```

Figure 4-16. *Running custom Contiki shell API*

Custom Contiki-NG Shell

Contiki-NG applies shell with a different approach. To customize a shell, we can add our shell command to the `shell-commands.c` file. You can find that file in the `<contiki-ng-root>/os/services/shell` folder. You can see it in Figure 4-17.

We add a new shell command to the `shell-commands.c` file. We define a “hello” command. We print the message "`Hi, this is a custom shell`" to Terminal. Write this code:

```
static
PT_THREAD(cmd_hello(struct pt *pt, shell_output_func output,
char *args))
{
  PT_BEGIN(pt);
  SHELL_OUTPUT(output, "Hi, this custom shell\n")

  PT_END(pt);
}
```

Next, we also register our shell in the `shell_command_t shell_commands` struct. We define the shell name, method call, and description. For instance, you can see the code for our custom NG-shell here:

```
struct shell_command_t shell_commands[] = {
  { "hello",   cmd_hello,   "'> hello': say hello" },
  { "help",    cmd_help,    "'> help': Shows this help" },
  { "reboot",  cmd_reboot,  "'> reboot': Reboot the board by
                                          watchdog_reboot()" },

  ...
};
```

Save all files.

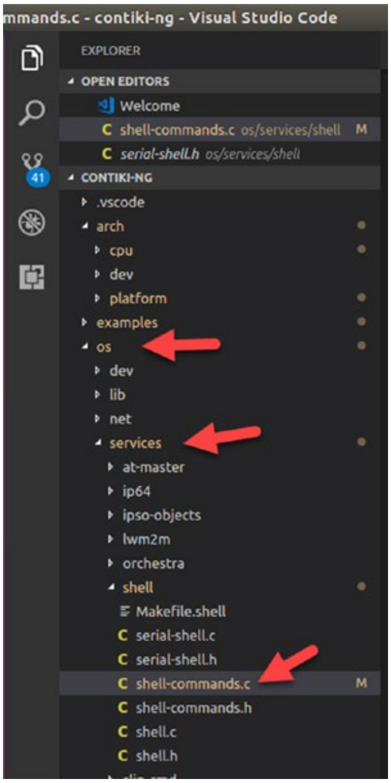


Figure 4-17. *NG shell in Contiki-NG source code*

Now, you can use the NG shell on your project. For instance, we can use a hello-world project and enable the Contiki-NG shell. We only enable shell service on `Makefile`:

```
MODULES += os/services/shell
```

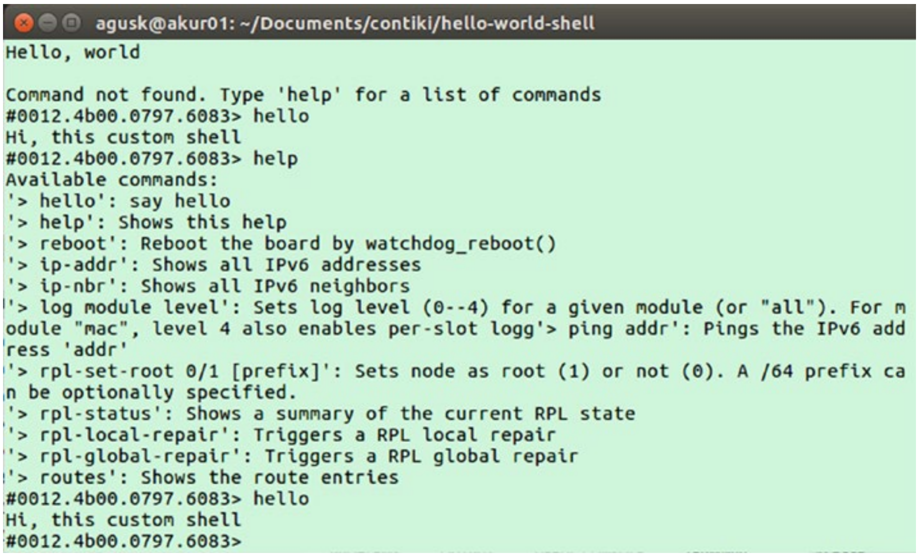
After that, we compile and flash this program onto the Contiki-NG mote. You can now remote into the Contiki mote Terminal using `mote login`. For instance, I remote access my TI LaunchPad CC2650 using this command:

```
$ make login TARGET=srf06-cc26xx PORT=/dev/ttyUSB0
```

You should change TARGET and PORT to reflect your Contiki board. Please press the Reset button on the Contiki mote if you do not see anything in Terminal. Now, you can test your own shell:

```
shell> help
shell> hello
```

After calling our NG shell, we can see the shell response. You can see my shell output in Figure 4-18.



```
agusk@akur01: ~/Documents/contiki/hello-world-shell
Hello, world

Command not found. Type 'help' for a list of commands
#0012.4b00.0797.6083> hello
Hi, this custom shell
#0012.4b00.0797.6083> help
Available commands:
'> hello': say hello
'> help': Shows this help
'> reboot': Reboot the board by watchdog_reboot()
'> ip-addr': Shows all IPv6 addresses
'> ip-nbr': Shows all IPv6 neighbors
'> log module level': Sets log level (0--4) for a given module (or "all"). For m
odule "mac", level 4 also enables per-slot logg'> ping addr': Pings the IPv6 add
ress 'addr'
'> rpl-set-root 0/1 [prefix]': Sets node as root (1) or not (0). A /64 prefix ca
n be optionally specified.
'> rpl-status': Shows a summary of the current RPL state
'> rpl-local-repair': Triggers a RPL local repair
'> rpl-global-repair': Triggers a RPL global repair
'> routes': Shows the route entries
#0012.4b00.0797.6083> hello
Hi, this custom shell
#0012.4b00.0797.6083>
```

Figure 4-18. *Running custom NG shell on TI LaunchPad CC260*

Communication among Contiki Motes

In this section, we will build a communication among Contiki-NG motes. There are a lot of methods for communicating among Contiki-NG motes. To show how to communicate among Contiki motes, we use broadcast via UDP protocol in Contiki-NG OS. UDP is a communication stack that provides a set of lightweight communication primitives ranging from local-area broadcast to reliable network flooding.

For this demo, we need at least two Contiki-NG motes. One mote will act as a sender and the other mote will be a receiver. You can see our demo scenario in Figure 4-19.

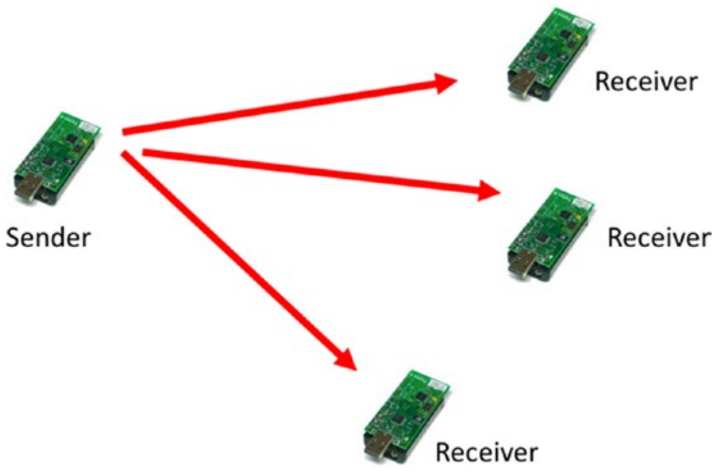


Figure 4-19. *Communication among Contiki-NG motes*

Our demo scenario is that a mote sends data to all motes. If a mote receives data, it will be shown in Terminal. We use a program sample from Contiki-NG.

Sending Broadcast Messages

The objective of a mote sender is to broadcast data to other motes. For this demo, we use the `simple-udp` module that is located in the `<contiki-ng-root>/os/net` folder. We can use the `simple_udp_sendto()` function to broadcast a message. This method is defined in the `simple-udp.h` header file:

```
int simple_udp_sendto_port(struct simple_udp_connection *c,
                          const void *data, uint16_t datalen,
                          const uip_ipaddr_t *to, uint16_t to_
                          port);
```

Note:

- `simple_udp_connection` is simple-udp object
- `data` is data that will be sent
- `datalen` is length of data
- `to` is ip address of target
- `to_port` is the port of the target

For instance, we send data to a specific IP address:

```
simple_udp_sendto(&udp_conn, &count, sizeof(count), &dag->dag_id);
```

Receiving Broadcast Messages

A mote receiver listens for an incoming message that is sent by a mote sender. To build a mote receiver, we can listen for broadcast messages by creating a callback/event function. We can use `simple_udp_register()` to register our callback function.

For instance, we listen for incoming broadcast messages using this code:

```
static void
udp_rx_callback(struct simple_udp_connection *c,
         const uip_ipaddr_t *sender_addr,
         uint16_t sender_port,
         const uip_ipaddr_t *receiver_addr,
         uint16_t receiver_port,
         const uint8_t *data,
         uint16_t datalen)
{
  unsigned count = *(unsigned *)data;
  LOG_INFO("Received response %u from ", count);
  LOG_INFO_6ADDR(sender_addr);
  LOG_INFO_("\n");
}

...

simple_udp_register(&udp_conn, UDP_CLIENT_PORT, NULL,
                      UDP_SERVER_PORT, udp_rx_callback);
```

Demo: Middleware Application

Now, we implement our sender and receiver program for Contiki-NG motes. We use a program sample from Contiki-NG, rpl-udp. You can find this project in the `<contiki-ng-root>/examples/` folder.

The rpl-udp project consists of two programs, `udp-client.c` and `udp-server.c`. The UDP client app (`udp-client.c`) will send and receive broadcast messages. The UDP server (`udp-server.c`) will listen for incoming broadcast messages.

In the `Makefile` file, we configure our project and Contiki-NG paths. Write these scripts for the `Makefile` file:

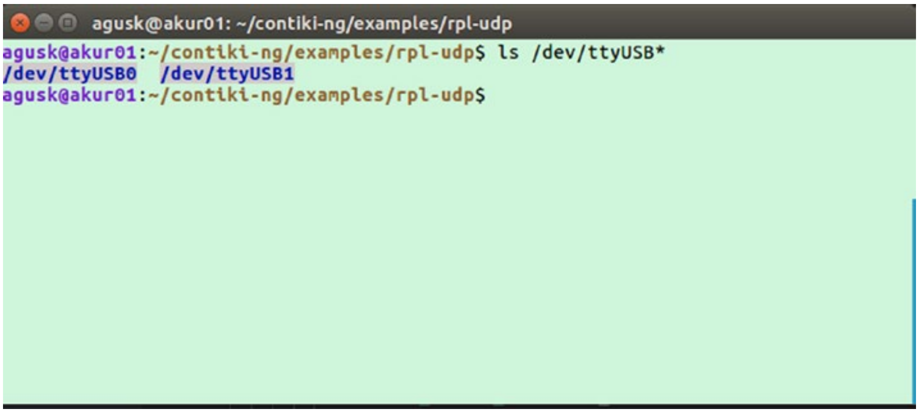
```
all: udp-client udp-server

.PHONY: renode
renode: all
ifneq ($(TARGET),cc2538dk)
        $(error Only the cc2538dk TARGET is supported for
        Renode demo scripts)
endif
ifndef SCRIPT
        $(warning SCRIPT not defined! Using "rpl-udp.resc" as
        default)
        renode rpl-udp.resc
else
ifeq ($(wildcard $(SCRIPT)),)
       $(error SCRIPT "$(SCRIPT)" does not exist!)
endif
       renode $(SCRIPT)
endif

CONTIKI=../..
include $(CONTIKI)/Makefile.include
```

Save all files.

Since we need at least two Contiki-NG motes, we should know the serial ports that are used by our Contiki-NG motes. You can check this using this command:

```
$ ls /dev/ttyUSB*
```

You should see a list of serial ports that are used by the Contiki-NG motes. For instance, my two TelosB motes are detected, shown in Figure 4-20.



```
agusk@akur01: ~/contiki-ng/examples/rpl-udp
agusk@akur01:~/contiki-ng/examples/rpl-udp$ ls /dev/ttyUSB*
/dev/ttyUSB0  /dev/ttyUSB1
agusk@akur01:~/contiki-ng/examples/rpl-udp$
```

Figure 4-20. *Getting a list of connected Contiki-NG motes*

To compile and upload the program to a specific Contiki-NG mote, we should pass `MOTES` with the serial port of the targeted Contiki-NG mote. For instance, we flash a program to a Contiki mote on serial port `/dev/ttyUSB0`. You can type these commands:

```
$ make TARGET=sky
$ make TARGET=sky savetarget
$ make udp-client.upload TARGET=sky MOTES=/dev/ttyUSB0
```

For the second Contiki-NG mote, you can type these commands:

```
$ make udp-server.upload TARGET=sky MOTES=/dev/ttyUSB1
```

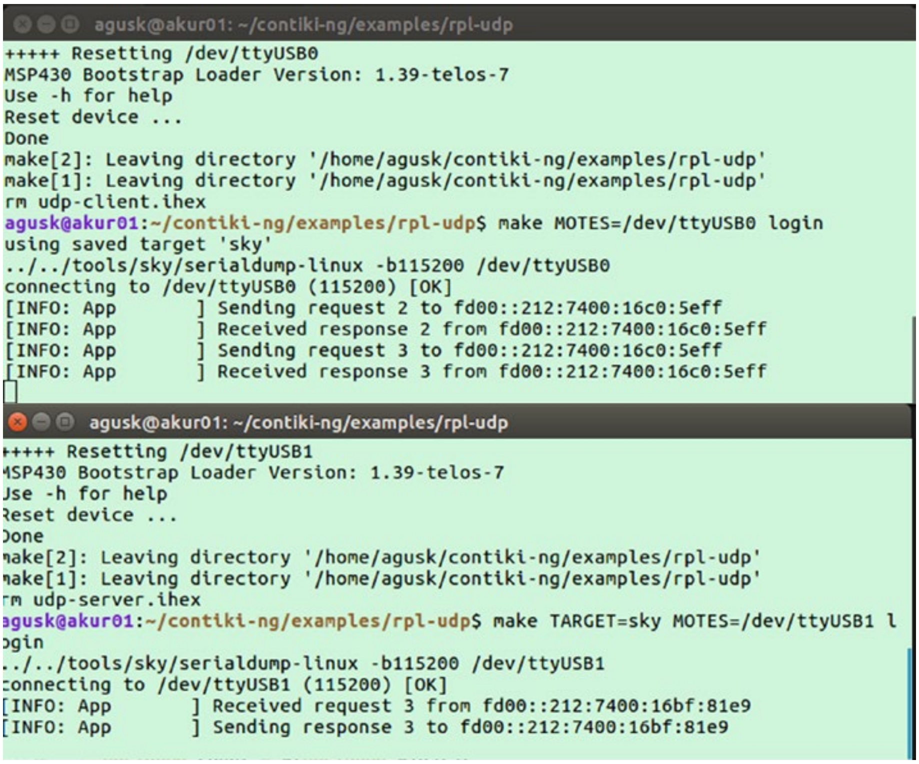
After all programs are uploaded to the Contiki-NG motes, we can monitor the data exchange among Contiki-NG motes. For Contiki-NG mote 1, we can monitor messages using this command:

```
$ make login TARGET=sky MOTES=/dev/ttyUSB0
```

For Contiki-NG mote 2, we can execute this command to see exchange data in Terminal. Type this command:

```
$ make login TARGET=sky MOTES=/dev/ttyUSB1
```

You should see an incoming message in Terminal. You can see it in Figure 4-21.



```
+++++ Resetting /dev/ttyUSB0
MSP430 Bootstrap Loader Version: 1.39-telos-7
Use -h for help
Reset device ...
Done
make[2]: Leaving directory '/home/agusk/contiki-ng/examples/rpl-udp'
make[1]: Leaving directory '/home/agusk/contiki-ng/examples/rpl-udp'
rm udp-client.ihex
agusk@akur01:~/contiki-ng/examples/rpl-udp$ make MOTES=/dev/ttyUSB0 login
using saved target 'sky'
../../tools/sky/serialdump-linux -b115200 /dev/ttyUSB0
connecting to /dev/ttyUSB0 (115200) [OK]
[INFO: App       ] Sending request 2 to fd00::212:7400:16c0:5eff
[INFO: App       ] Received response 2 from fd00::212:7400:16c0:5eff
[INFO: App       ] Sending request 3 to fd00::212:7400:16c0:5eff
[INFO: App       ] Received response 3 from fd00::212:7400:16c0:5eff
```

```
++++ Resetting /dev/ttyUSB1
ISP430 Bootstrap Loader Version: 1.39-telos-7
Jse -h for help
Reset device ...
Done
nake[2]: Leaving directory '/home/agusk/contiki-ng/examples/rpl-udp'
nake[1]: Leaving directory '/home/agusk/contiki-ng/examples/rpl-udp'
rm udp-server.ihex
agusk@akur01:~/contiki-ng/examples/rpl-udp$ make TARGET=sky MOTES=/dev/ttyUSB1 l
ogin
../../tools/sky/serialdump-linux -b115200 /dev/ttyUSB1
connecting to /dev/ttyUSB1 (115200) [OK]
[INFO: App       ] Received request 3 from fd00::212:7400:16bf:81e9
[INFO: App       ] Sending response 3 to fd00::212:7400:16bf:81e9
```

Figure 4-21. *Running Contiki-NG application on mote 1 and mote 2*

Middleware Application for Contiki-NG

In this section, we will explore using middleware for a Contiki-NG application. In our scenario, WSN motes will broadcast sensor data. Then, we will use a Java tool application from Contiki-NG to read these sensor data on a computer. The result of reading this data will be displayed in Terminal.

Let's build!

What Is Middleware?

Middleware is a “bridge” application that connects Contiki-NG motes to other systems in internal and external networks. A sink can be represented as middleware. You can see a general architecture scenario of middleware for a Contiki-NG application in Figure 4-22.

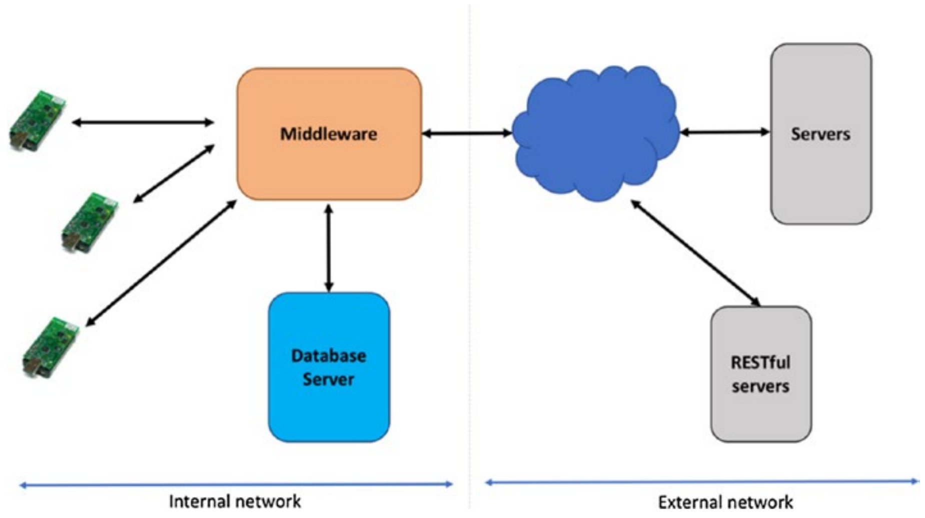


Figure 4-22. *General scenario model of middleware for Contiki-NG*

Implementing middleware for a Contiki-NG application could enhance Contiki-NG’s capabilities. As you know, Contiki-NG applications have a limitation in protocol stacks since they have limited hardware resources. Middleware can act as a bridge to connect Contiki-NG motes to other systems, such as database servers, external servers, and RESTful servers.

Middleware Architecture for Contiki-NG

In this section, we will build simple middleware for a Contiki-NG application. For this demo scenario, the middleware will listen for sensor data and print them to Terminal using Python. A general design for our demo is shown in Figure 4-23.

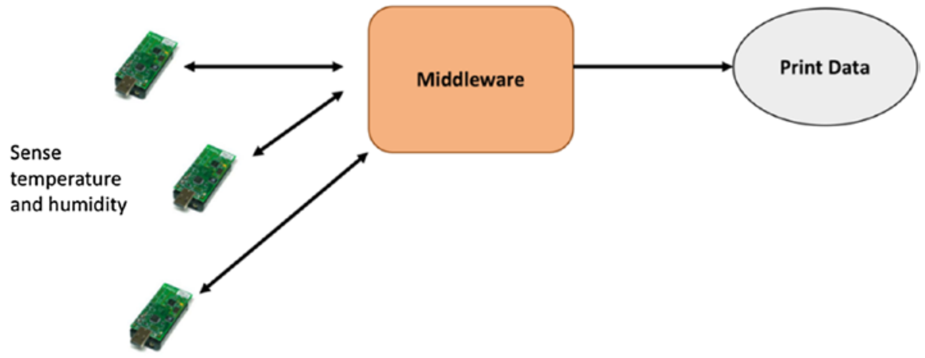


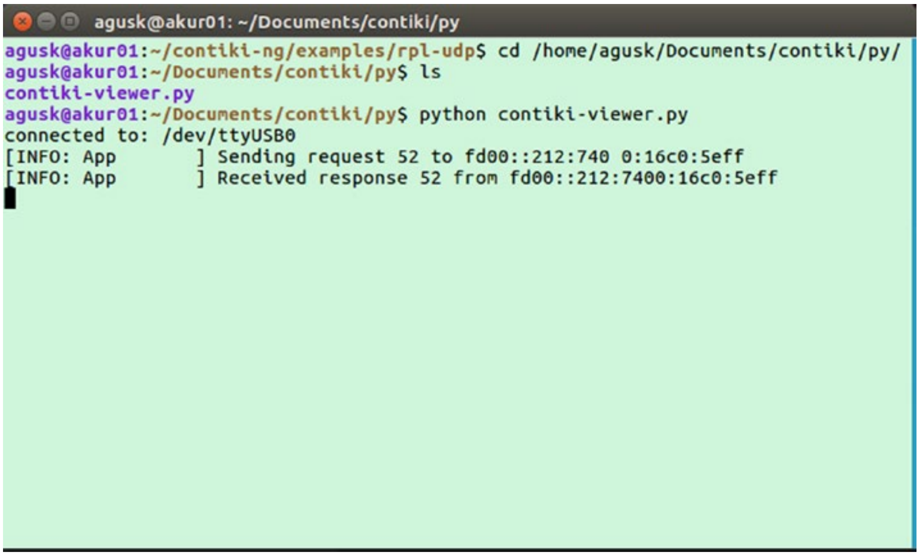
Figure 4-23. *Middleware architecture for demo*

Implementation

To implement our demo, we use our previous program, rpl-udp (`<contiki-ng_root/examples/rpl-udp`), to be flashed into the Contiki-NG motes. We also use a previous Python program (section: "Access Contiki Motes via Serial") to listen on the serial port `contiki-viewer.py`.

Testing

First, we compile the program and upload it to the motes. For instance, I have two WSN motes that are attached on serial ports `/dev/USB0` and `/dev/USB1`. Then, we run `contiki-viewer.py` with a specific port. You can see the program output in Figure 4-24. In the next chapter, we will work more with middleware.



```
agusk@akur01: ~/Documents/contiki/py
agusk@akur01:~/contiki-ng/examples/rpl-udp$ cd /home/agusk/Documents/contiki/py/
agusk@akur01:~/Documents/contiki/py$ ls
contiki-viewer.py
agusk@akur01:~/Documents/contiki/py$ python contiki-viewer.py
connected to: /dev/ttyUSB0
[INFO: App       ] Sending request 52 to fd00::212:740 0:16c0:5eff
[INFO: App       ] Received response 52 from fd00::212:7400:16c0:5eff
```

Figure 4-24. *Listening for incoming message from Python*

Summary

We have learned to communicate among Contiki-NG motes. We also developed an application to communicate with Contiki-NG motes from a computer. Finally, we built simple middleware for a Contiki-NG application using a Python application tool.

In the next chapter, we will learn to focus on sensing and actuating in Contiki-NG motes.

CHAPTER 5

Sensing and Actuating

Sensing and actuating are core activities in the Wireless Sensor Network lifecycle. Most WSN makers build WSN motes that include sensor or/and actuator devices. In this chapter, we will explore various sensor and actuator devices. Moreover, we will build a Contiki-NG program to access these sensor devices and control the actuator devices.

The following is a list of topics we will cover in this chapter:

- What are sensing and actuating?
- Reviewing sensors and actuators
- Sensing in Contiki-NG
- Actuating in Contiki-NG
- Customizing sensor and actuator devices

What Are Sensing and Actuating?

Sensing and actuating are two common terms that are used in embedded topics. In the WSN context, sensing is a process that converts a physical object to digital data. For instance, sensing temperature. The sensor device senses the environment's temperature and then converts it to digital form. Actuating is a process in which the MCU sends digital data to an actuator device to perform some tast, such as turning on LED lights, sounds, or a motor.

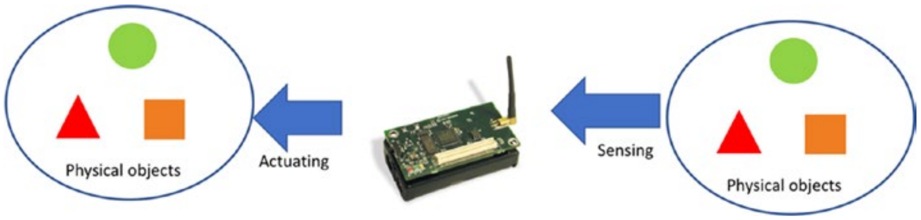


Figure 5-1. *Sensing and actuating in a WSN mote*

Sensing and actuating are shown in Figure 5-1. Sensor devices that are attached to a WSN mote will sense and then convert the information to digital data form. A WSN mote also can send digital data to the outside environment through actuator devices. Both sensor and actuator devices can communicate to the MCU via I/O interfaces. These interfaces provide various protocols depending on how they are implemented. You can see a communication model in Figure 5-2.

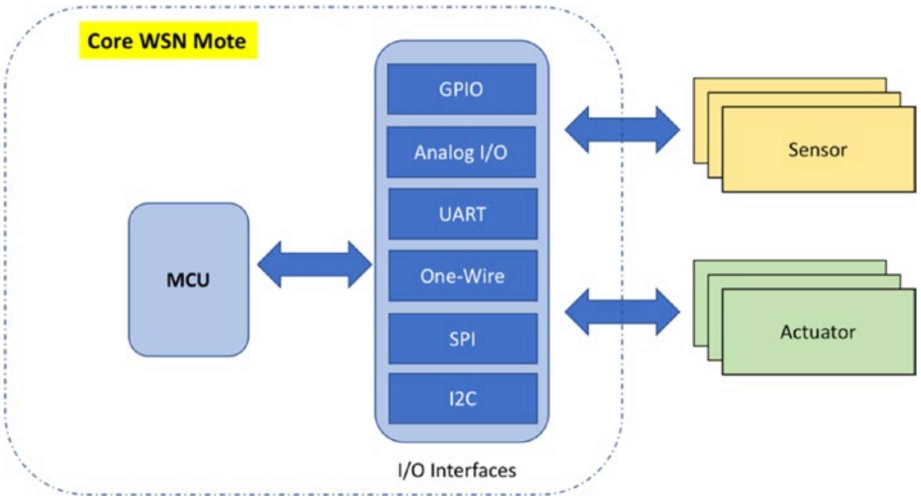


Figure 5-2. *Communication model for sensor/actuator devices and MCU*

We will start to explore sensor and actuator devices in the next section. Then, we will develop a Contiki-NG program for accessing those devices.

Review Sensor and Actuator Devices

In this section, we will explore common sensor and actuator devices that are used in embedded development environments, including in real applications. All sensor and actuator devices may be found in your local store. However, you can buy them in online stores such as Element14, Digikey, Mouser, SparkFun, Adafruit, DFRobot, SeeedStudio, and more. You can also find them on cheap online stores from China, like Alibaba, Aliexpress, Banggood, and DealeXtreme.

We will now review some sensor and actuator devices that are easier to find. Sensor device samples are temperature, humidity, soil moisture, and gas sensor. Actuator device samples can be LED, active buzzer, and motor. We will check them in the next section.

Temperature and Humidity

Temperature and humidity sensors are used to measure current environment temperature and humidity levels. Some manufactures make these sensors into one chip, but others are still available in separation sensors for temperature and humidity.

Most WSN motes are designed to include these temperature and humidity sensors. This is useful for our development and testing. We can verify that our program performs sensing and actuating. One example is the SHT1x (SHT10, SHT11, SHT15) chip from Sensirion. You can read its datasheet at `https://www.sparkfun.com/datasheets/Sensors/SHT1x_datasheet.pdf`. SparkFun provides the SHT15 sensor in a module that is ready to use. It's the SparkFun Humidity and Temperature Sensor

Breakout—SHT15. This product can be bought on the SparkFun website at https://www.sparkfun.com/products/13683. You can see the module in Figure 5-3.

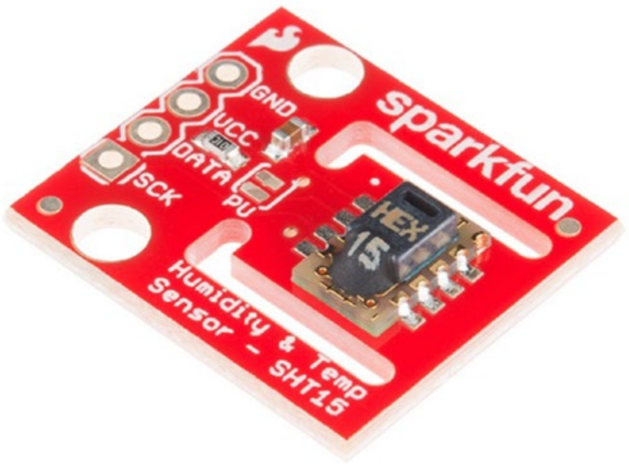


Figure 5-3. *SparkFun Humidity and Temperature Sensor Breakout—SHT15*

In general, SHT1x provides two-wire pins to be used to access sensor data. If you see a SparkFun Humidity and Temperature Sensor Breakout (Figure 5-3), this module has four pins: VCC, GND, DATA, and SCK. We can develop a program to access this sensor data from MCU.

We also can use a low-cost humidity and temperature sensor. It's the DHT22 module. This sensor is easier to find. You can check it out on the SparkFun website at https://www.sparkfun.com/products/10167; it is called Humidity and Temperature Sensor—RHT03 (DHT22). The DHT22 sensor provides a single-wire digital interface that is used to access sensor data for temperature and humidity. The DHT22 sensor form is shown in Figure 5-4.

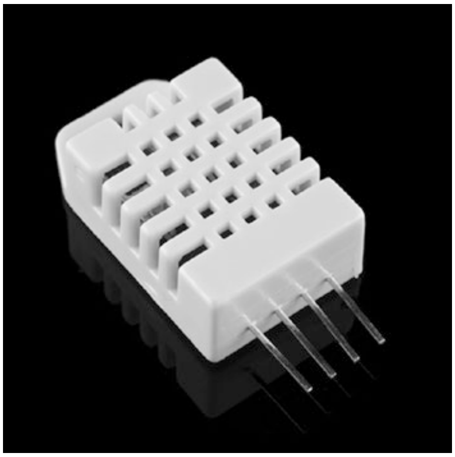


Figure 5-4. *Humidity and Temperature Sensor—RHT03 (DHT22)*

Soil Moisture

A soil moisture sensor can be used to measure the moisture level in soil. This sensor can be applied in monitoring systems for gardens. There are many soil-moisture models that you can use in your design. One with a low cost is a Soil Moisture Sensor from SparkFun, found at `https://www.sparkfun.com/products/13322`. The SparkFun Soil Moisture Sensor can be attached via an analog pin (ADC pin) to obtain the moisture level. You can see a SparkFun Soil Moisture Sensor in Figure 5-5.

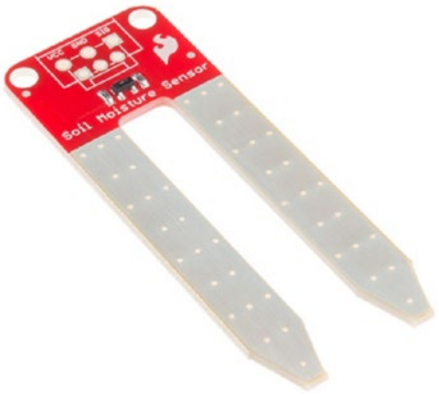


Figure 5-5. *SparkFun Soil Moisture Sensor*

Gas Sensor

In some scenarios, you may need to monitor for gas such as carbon monoxide (CO). You can attach a carbon monoxide sensor to a WSN mote through an analog pin so as to detect it. One such sensor is Carbon Monoxide Sensor (MQ-7). This sensor can detect gas concentrations anywhere from 20 to 2000 ppm. You can find it on the SparkFun website at `https://www.sparkfun.com/products/9403`. Figure 5-6 shows the Carbon Monoxide Sensor (MQ-7). Further information about this gas sensor (MQ-7) can be found at `https://cdn.sparkfun.com/datasheets/Sensors/Biometric/MQ-7%20Ver1.3%20-%20Manual.pdf`.

Figure 5-6. *Carbon Monoxide Sensor (MQ-7)*

LED

An LED is a simple actuator device. It can be used for lighting indicator and notification, processing status, or indicating a certain state. There are various models and colors for LEDs. You can choose it to fit with your case. Figure 5-7 shows a sample LED.

Figure 5-7. *A LED with red color in 5mm size (Source: `https://www.sparkfun.com/products/9590`)*

Active Buzzer

Sometimes you need an actuator that generates a continuous sound to inform the user of a particular state, such as low power on battery, problem on a certain system module, or waiting for an action. An active buzzer can be used as an actuator device to indicate a certain notification. This actuator is low cost and easier to find.

In general, an active buzzer has two pins, GND and SIG. It's easy to use because we just send a digital value (3.3V or 5V) on the SIG pin to generate a continuous sound. The sound will be stopped if we set 0V (GND) on the SIG pin. You can see this actuator in Figure 5-8.

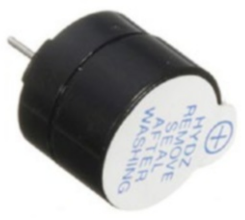


Figure 5-8. *Active buzzer*

Motor

To control mechanical stuff, you may need a motor that is designed for the MCU to make a movement or rotation. There are various motor models. A servo motor is a basic motor that can be integrated with a WSN mote. You should keep in mind that some motor models need a lot of power, and they should not get that power from your WSN mote. You can use an external power adapter for your motor. The manufacturer also provides a motor driver that addresses motor power issues.

One servo motor is the Hitec HS-5035HD servo with Ultra Nano Size. You can buy it on the SparkFun website at `https://www.sparkfun.com/products/14210`. Figure 5-9 shows a Hitec HS-5035HD servo.

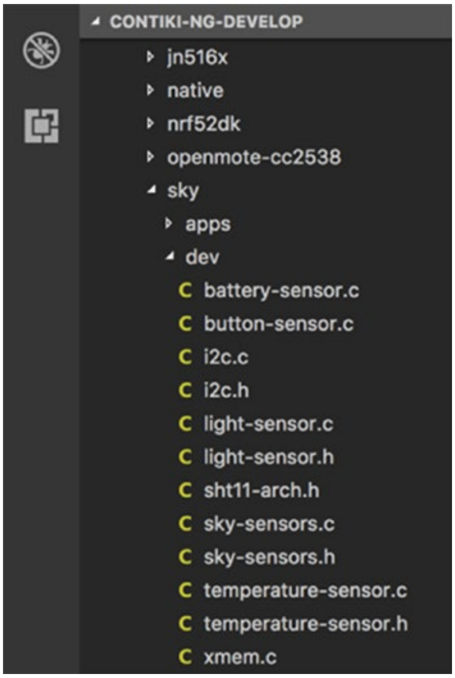
Figure 5-9. *Hitec HS-5035HD servo with Ultra Nano Size*

Sensing in Contiki-NG

Each sensor in Contiki-NG should implement `sensors.h` from the `<contiki-ng-root>/os/lib` folder. We can access the sensor device library using the following code:

```
SENSORS_ACTIVATE(sensor_xyz);
...
val = sensor_xyz.value(SENSOR_XYZ_TYPE);
```

`sensor_xyz` is a defined variable for the sensor device. This is a part of each Contiki-NG device platform. Each sensor device has sensor types that will be called on the `value()` method. Your sensor code (`*.c` and `*.h`) should be put in the `dev/` folder from the Contiki-NG platfom. You can see a list of sensor codes in Figure 5-10.



```
CONTIKI-NG-DEVELOP
    jn516x
    native
    nrf52dk
    openmote-cc2538
    sky
      apps
      dev
        battery-sensor.c
        button-sensor.c
        i2c.c
        i2c.h
        light-sensor.c
        light-sensor.h
        sht11-arch.h
        sky-sensors.c
        sky-sensors.h
        temperature-sensor.c
        temperature-sensor.h
        xmem.c
```

Figure 5-10. *Sensor and actuator libraries for Sky platform*

In the next section, we will build a simple demo for sensing using the existing sensor in Contiki-NG. I use a TelosB for testing.

Demo

We will build a Contiki-NG application to read the current temperature and humidity via a Contiki-NG mote. For testing, I use TelosB as Contiki-NG mote. This board provides an SHT11 sensor that can sense temperature and humidity. You can read the sensor datasheet at `https://www.sensirion.com/en/environmental-sensors/humidity-sensors/digital-humidity-sensors-for-accurate-measurements/`.

For this demo, we will build the scenario that is shown in Figure 5-11. A Contiki-NG mote with sensor device is attached to a computer. We will sense temperature and humidity via the SHT11 sensor. After acquiring the temperature, the mote will send this sensor data to a serial port on the computer. We will print this sensor data in Terminal by reading the serial port.

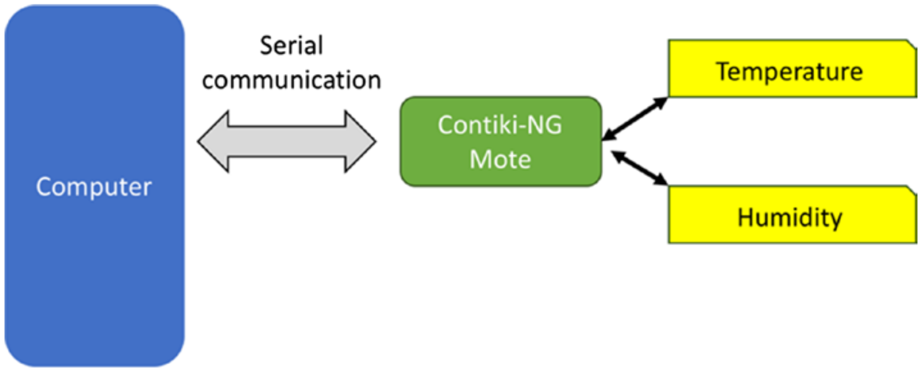


Figure 5-11. *Sensing demo scenario*

Creating a Project

To create a new project on Contiki-NG, you can create a folder, for instance, `sensing`. Then, add `sensing.c` and `Makefile` files. Our program that uses the sensor device will be implemented in the `sensing.c` file. We define our project configuration in the `Makefile` file.

The following is the content of the Makefile file:

```
CONTIKI_PROJECT = sensing
all: $(CONTIKI_PROJECT)

CONTIKI = /home/agusk/contiki-ng/
include $(CONTIKI)/Makefile.include
```

Change `CONTIKI` to your Contiki-NG path.

Next, we will write a Contiki-NG program on the `sensing.c` file.

Writing a Program

We will build a Contiki-NG program to acquire the temperature every five seconds. We use `etimer` to implement our timer object.

The following is the complete program in the `sensing.c` file:

```
#include "contiki.h"
#include "dev/sht11/sht11-sensor.h"

#include <math.h>
#include <stdio.h> /* For printf() */
/*---------------------------------------------------------------*/
PROCESS(sensing_process, "Sensing process");
AUTOSTART_PROCESSES(&sensing_process);
/*---------------------------------------------------------------*/
PROCESS_THREAD(sensing_process, ev, data)
{
  static struct etimer et;
  static int val;
  static float s = 0;
  static int dec;
  static float frac;

  PROCESS_BEGIN();

  printf("Demo sensing...\n");
  while(1)
  {
        etimer_set(&et, CLOCK_SECOND * 5);
    SENSORS_ACTIVATE(sht11_sensor);

        PROCESS_WAIT_EVENT_UNTIL(etimer_expired(&et));

    val = sht11_sensor.value(SHT11_SENSOR_TEMP);
    if(val != -1)
    {
      s= ((0.01*val) - 39.60);
      dec = s;
      frac = s - dec;
      // print float data
      printf("Temperature=%d.%02u C . VAL=%d\n", dec, (unsigned
      int)(frac * 100),val);
    }

    val=sht11_sensor.value(SHT11_SENSOR_HUMIDITY);
    if(val != -1)
    {
      s= (((0.0405*val) - 4) + ((-2.8 *
      0.000001)*(pow(val,2))));
      dec = s;
      frac = s - dec;
      // print float data
      printf("Humidity=%d.%02u %% . VAL=%d\n", dec, (unsigned
      int)(frac * 100),val);
    }

    etimer_reset(&et);
    SENSORS_DEACTIVATE(sht11_sensor);

  }

  PROCESS_END();
}
/*---------------------------------------------------------------------------*/
```

How does it work?

Firstly, we activate the timer and our SHT11 sensor on the TelosB:

```
etimer_set(&et, CLOCK_SECOND * 5);
SENSORS_ACTIVATE(sht11_sensor);
```

```
PROCESS_WAIT_EVENT_UNTIL(etimer_expired(&et));
```

After `etimer` has raised the time, we sense temperature by calling `value()` from the `sht11_sensor` object and passing the `SHT11_SENSOR_TEMP` parameter. Since we face displaying float data, we calculate decimal and fraction separately:

```
val = sht11_sensor.value(SHT11_SENSOR_TEMP);
if(val != -1)
{
  s= ((0.01*val) - 39.60);
  dec = s;
  frac = s - dec;
  // print float data
  printf("Temperature=%d.%02u C . VAL=%d\n", dec, (unsigned
  int)(frac * 100),val);
}
```

We also do a similar task to sense humidity. We pass `SHT11_SENSOR_HUMIDITY` to read humidity from sensor:

```
val=sht11_sensor.value(SHT11_SENSOR_HUMIDITY);
if(val != -1)
{
  s= (((0.0405*val) - 4) + ((-2.8 * 0.000001)*(pow(val,2))));
  dec = s;
  frac = s - dec;
  // print float data
  printf("Humidity=%d.%02u %% . VAL=%d\n", dec, (unsigned int)
  (frac * 100),val);
}
```

Last, we reset our timer and sensor objects:

```
etimer_reset(&et);
SENSORS_DEACTIVATE(sht11_sensor);
```

Testing

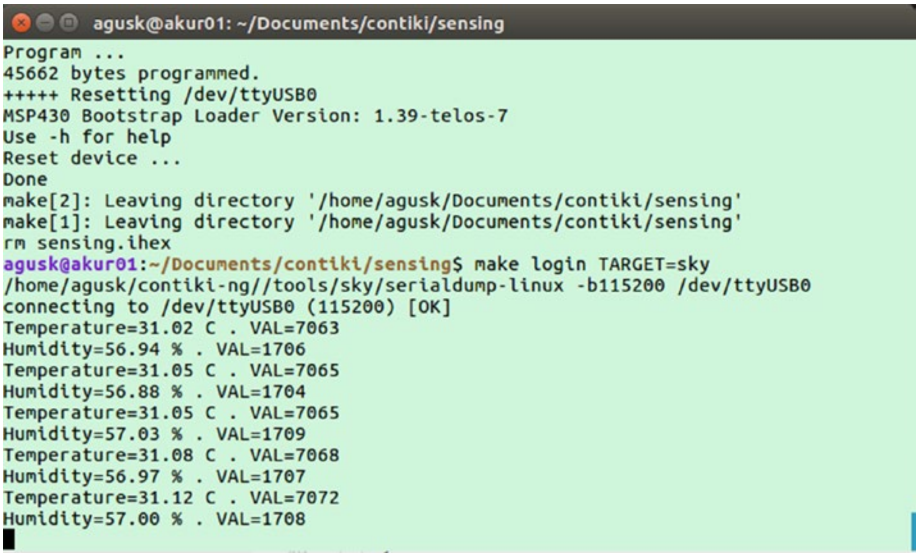
Now, you can test the program. You should compile and deploy this program into Contiki-NG:

```
$ make TARGET=sky
$ make TARGET=sky savetarget
$ make sensing.upload TARGET=sky
```

After uploading a program into Contiki-NG, we try to monitor the serial output from the Contiki-NG mote. You can type this command to do so:

```
$ make login TARGET=sky
```

If it succeeds, you should see the current temperate and humidity values in Terminal. You can see my program output in Figure 5-12.



```
agusk@akur01: ~/Documents/contiki/sensing
Program ...
45662 bytes programmed.
+++++ Resetting /dev/ttyUSB0
MSP430 Bootstrap Loader Version: 1.39-telos-7
Use -h for help
Reset device ...
Done
make[2]: Leaving directory '/home/agusk/Documents/contiki/sensing'
make[1]: Leaving directory '/home/agusk/Documents/contiki/sensing'
rm sensing.ihex
agusk@akur01:~/Documents/contiki/sensing$ make login TARGET=sky
/home/agusk/contiki-ng//tools/sky/serialdump-linux -b115200 /dev/ttyUSB0
connecting to /dev/ttyUSB0 (115200) [OK]
Temperature=31.02 C . VAL=7063
Humidity=56.94 % . VAL=1706
Temperature=31.05 C . VAL=7065
Humidity=56.88 % . VAL=1704
Temperature=31.05 C . VAL=7065
Humidity=57.03 % . VAL=1709
Temperature=31.08 C . VAL=7068
Humidity=56.97 % . VAL=1707
Temperature=31.12 C . VAL=7072
Humidity=57.00 % . VAL=1708
```

Figure 5-12. *Program output on sensing application*

Actuating in Contiki-NG

In this section, we will learn how to work with actuating in Contiki-NG. There are a lot of actuator devices that you can use with Contiki-NG. For this demo, I will use a button and an LED as actuator devices. In general, these actuator devices are available on some Contiki-NG motes.

This demo is shown in Figure 5-13. If the user presses the button, the LED will be toggled. I use TelosB for this demo as it already has a button and an LED.

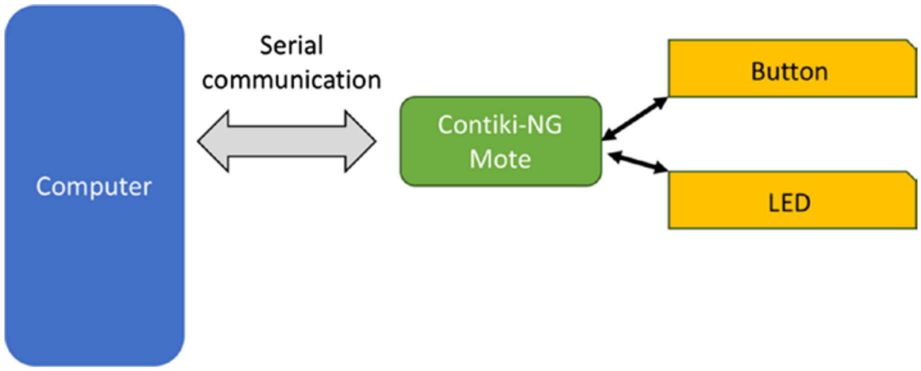


Figure 5-13. *Actuating demo scenario*

Creating a Project

You can start a new project by creating a folder, called `actuating`. Then, add Makefile and `actuating.c` files. In the `Makefile` file, we configure our project. You can write the following `Makefile` content:

```
CONTIKI_PROJECT = actuating
all: $(CONTIKI_PROJECT)

CONTIKI = /home/agusk/contiki-ng/
include $(CONTIKI)/Makefile.include
```

Change `CONTIKI` to your Contiki-NG path.

Next, we will build a program in the `actuating.c` file.

Writing a Program

The program will listen for the pressed button from the user. If the user presses the button, we toggle the LED. The following is the content of the `actuating.c` file:

```
#include "contiki.h"
#include "leds.h"
#include "dev/button-sensor.h"

#include <stdio.h>
/*---------------------------------------------------------------------------*/
PROCESS(sensing_process, "Sensing process");
AUTOSTART_PROCESSES(&sensing_process);
/*---------------------------------------------------------------------------*/
PROCESS_THREAD(sensing_process, ev, data)
{
  PROCESS_BEGIN();

  printf("Demo actuating...\n");
  SENSORS_ACTIVATE(button_sensor);
  leds_off(LEDS_ALL);

  while(1)
  {
    PROCESS_WAIT_EVENT_UNTIL(ev == sensors_event &&
                            data == &button_sensor);

    leds_toggle(LEDS_BLUE);
  }
  SENSORS_DEACTIVATE(button_sensor);
  PROCESS_END();
}
/*---------------------------------------------------------------------------*/
```

How does it work?

First, we active the button by calling SENSOR_ACTIVATE(). We then turn all LEDs off for initialization.

```
SENSORS_ACTIVATE(button_sensor);
leds_off(LEDS_ALL);
```

Then, we wait for the button to be pressed by the user. We can use PROCESS_WAIT_EVENT_UNTIL() to detect the pressed button. We will toggle the LED after the button is pressed:

```
while(1)
{
  PROCESS_WAIT_EVENT_UNTIL(ev == sensors_event &&
                           data == &button_sensor);

  leds_toggle(LEDS_BLUE);
}
```

Testing

Now, you can test the program. You should compile and deploy this program into Contiki-NG:

```
$ make TARGET=sky
$ make TARGET=sky savetarget
$ make actuating.upload TARGET=sky
```

You can press a user button on the Contiki-NG mote. You will see an LED light up while you press the button. You can see the user button and the LED on a TelosB in Figure 5-14.

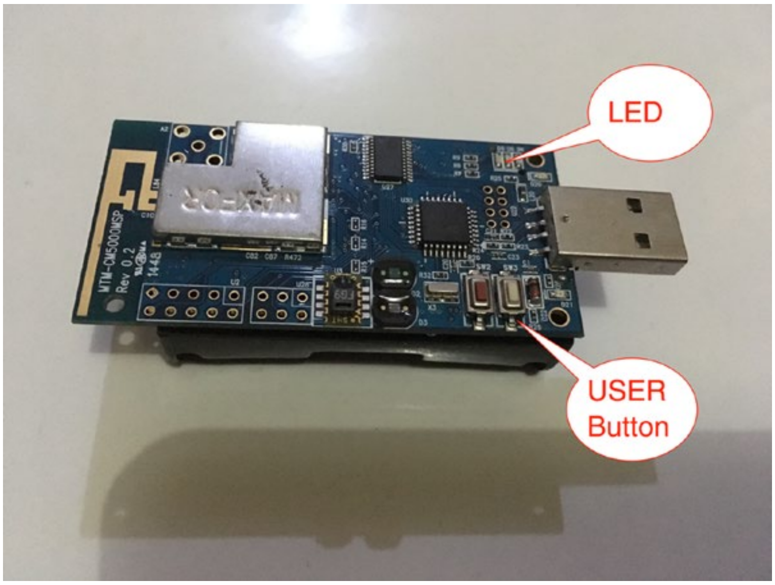


Figure 5-14. *User button and LED on TelosB*

Customizing Sensor and Actuator Devices

You probably want to expand your sensors and actuators on your Contiki-NG mote. In the real world, some Contiki-NG motes do not provide built-in sensors and actuators. Others only have one or two sensor devices.

In this section, we will explore how to add additional sensor and actuator devices to Contiki-NG motes.

Expansion Connector

Some Contiki-NG motes are designed to enable you to expand their board. One option is to provide an expansion connector. The board design exposes MCU pins in order to make additional external sensors, actuators, or other devices interact with the system.

For instance, TelosB has an expansion connector available to enable makers to attach sensors and actuators to the board. You can see it in Figure 5-15.

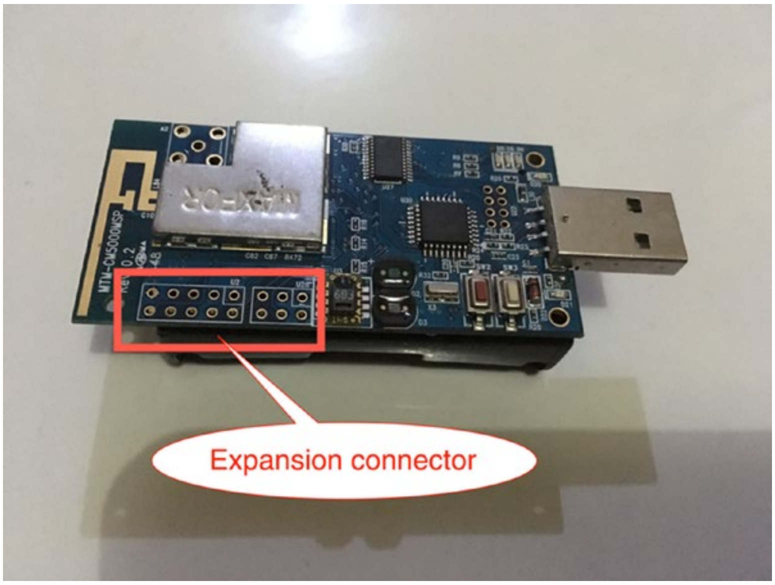


Figure 5-15. *Expansion connector on TelosB*

I bought my TelosB from ADVANTICSYS. This product is MTM-CM5000-MSP. Based on its document, found at `https://www.advanticsys.com/shop/mtmcm5000msp-p-14.html`, these expansion connectors are as depicted in Figure 5-16.

As seen in Figure 5-16, we can attach sensor and actuator devices to the mote. GPIO pins such as ADC and I2C are accessible from the main board. You can do wiring for your sensor and actuator devices.

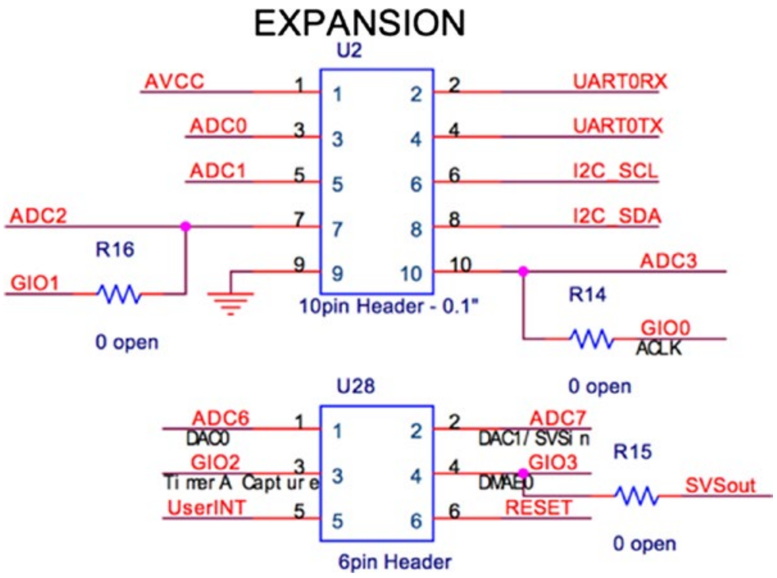


Figure 5-16. *Expansion connector pinout from TelosB*

Another board, such as Zoul from Zolertia, https://zolertia.io/zoul-module/, can be attached to your own board. Zolertia also provides a complete development kit, Firefly. You can develop Contiki-NG on top of the board. Further information about Firefly can be found at https://zolertia.io/product/firefly/. Figure 5-17 shows a form of the Firefly board.

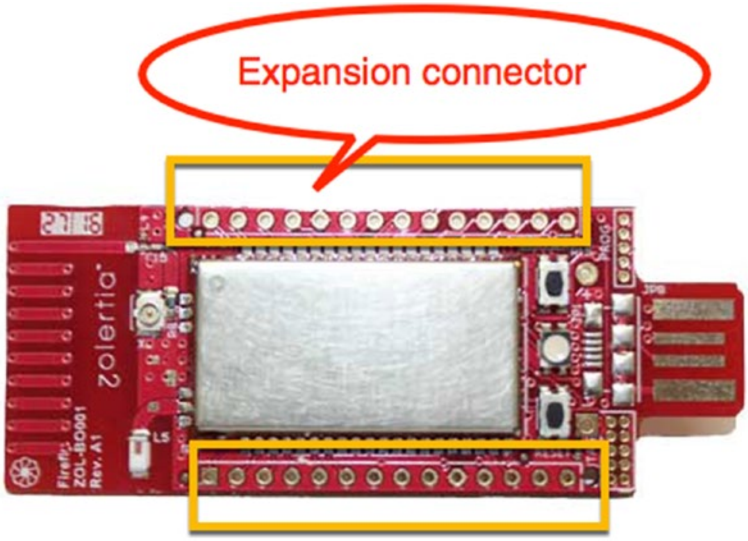


Figure 5-17. *Expansion connector on Firefly*

Sensor and Actuator Drivers for Contiki-NG

Each sensor or actuator device attached to Contiki-NG should provide an API driver. In this section, we will explore how to make device drivers for Contiki-NG.

Each Contiki-NG mote platform has a different development style. You should decide what Contiki-NG platform you will use for additional sensor and actuator devices. If you have a plan to develop sensors and actuators for all platforms, you can put your drivers at `<contiki-ng-root>/arch/dev`. Otherwise, you can put them at `<contiki-ng-root>/arch/platforms/<your-platform>`. You can see it in Figure 5-18.

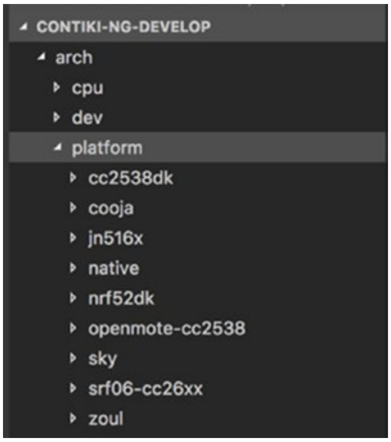


Figure 5-18. *Platform API on Contiki-NG*

For demo purposes, we will develop a driver for the Sky platform. We build a sensor that is attached into TelosB via an ADC0 pin. Next, we will write a driver program for the Sky platform.

We add two files, `mycustom-sensor.h` and `mycustom-sensor.c`. These files are put in the `<contiki-ng-root>/arch/platform/sky/dev` folder. You can see them in Figure 5-19. We extend our custom sensor driver from the `sensors.h` and `sky-sensors.h` files.

The following is the content of the `mycustom-sensor.h` file:

```
#ifndef MYCUSTOM_SENSOR_H_
#define MYCUSTOM_SENSOR_H_

#include "lib/sensors.h"

extern const struct sensors_sensor mycustom_sensor;

#define MY_CUSTOM_SENSOR 0

#endif /* MYCUSTOM_SENSOR_H_ */
```

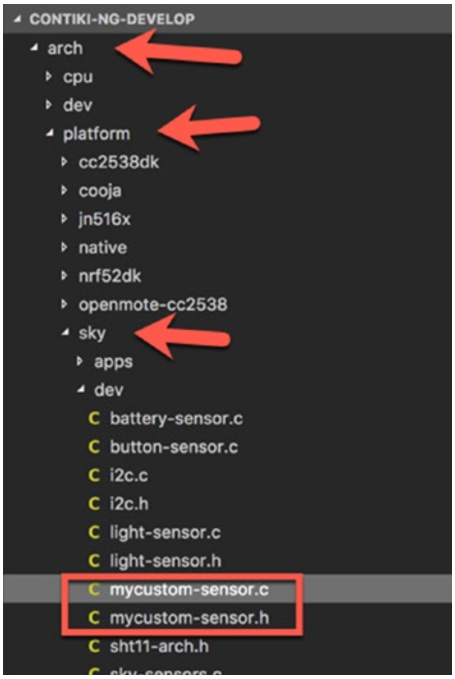


Figure 5-19. *Adding driver files into Sky platform*

Now we implement the `mycustom-sensor.c` file. The ADC0 pin is attached on ADC12MEM0. Since we implement `sky-sensors.h`, we should implement the `value()`, `configure()`, and `status()` methods.

The following is the content of the `mycustom-sensor.c` file:

```
#include "contiki.h"
#include "dev/mycustom-sensor.h"
#include "dev/sky-sensors.h"

#define INPUT_CHANNEL   (1 << INCH_11)
#define INPUT_REFERENCE SREF_0
#define MYCUSTOM_MEM    ADC12MEM0
```

```
const struct sensors_sensor mycustom_sensor;
/*---------------------------------------------------------------*/
static int
value(int type)
{
  switch(type) {
    case MY_CUSTOM_SENSOR:
        return MYCUSTOM_MEM;
  }

  return 0;
}
/*---------------------------------------------------------------*/
static int
configure(int type, int c)
{
  return sky_sensors_configure(INPUT_CHANNEL, INPUT_REFERENCE,
  type, c);
}
/*---------------------------------------------------------------*/
static int
status(int type)
{
  return sky_sensors_status(INPUT_CHANNEL, type);
}
/*---------------------------------------------------------------*/
SENSORS_SENSOR(mycustom_sensor, "MYCUSTOMSENSOR", value,
configure, status);
```

Last, we should add our driver file into the `Makefile.sky` file from the Sky platform. It is located at `<contiki-ng-root>/arch/platform/sky/Makefile.sky`. In our case, we move the `mycustom-sensor.c` file into the `Makefile.sky` file. You can see the bold code for adding the driver file here:

```
CONTIKI_TARGET_SOURCEFILES += contiki-sky-platform.c \
        sht11.c sht11-sensor.c light-sensor.c battery-sensor.c \
        button-sensor.c mycustom-sensor.c

include $(CONTIKI)/arch/platform/sky/Makefile.common

MODULES += os/net/mac os/net/mac/framer os/net \
           arch/dev/cc2420 arch/dev/sht11 arch/dev/ds2411 \
                                               os/storage/cfs
```

Your custom sensor driver is ready for Sky platform. You can use it as usual. For instance, you create a project by creating a folder, `custom-sensing`. Then, you add `Makefile` and `custom-sensing.c` files.

We will access our driver, `mycustom-sensor`, in our project. We use the same program from the sensing project but change it to use our own sensor. The following is the complete program for the `custom-sensing.c` file:

```
#include "contiki.h"
#include "dev/mycustom-sensor.h"

#include <stdio.h> /* For printf() */
/*---------------------------------------------------------------*/
PROCESS(sensing_process, "Sensing process");
AUTOSTART_PROCESSES(&sensing_process);
/*---------------------------------------------------------------*/
PROCESS_THREAD(sensing_process, ev, data)
{
  static struct etimer et;
  static int val;

  PROCESS_BEGIN();

  printf("Demo sensing...\n");
  while(1)
  {
          etimer_set(&et, CLOCK_SECOND * 5);
    SENSORS_ACTIVATE(mycustom_sensor);

          PROCESS_WAIT_EVENT_UNTIL(etimer_expired(&et));

    val = mycustom_sensor.value(MY_CUSTOM_SENSOR);
    if(val != -1)
    {
      printf("CUSTOM SENSOR VAL=%d\n",val);
    }

    etimer_reset(&et);
    SENSORS_DEACTIVATE(mycustom_sensor);

  }

  PROCESS_END();
}
```

Last, we should configure our project in the `Makefile` file:

```
CONTIKI_PROJECT = custom-sensing
all: $(CONTIKI_PROJECT)

CONTIKI = /home/agusk/contiki-ng/
include $(CONTIKI)/Makefile.include
```

Change the `CONTIKI` value to your Contiki-NG path. Now, you can compile and upload this program to TelosB:

```
$ make TARGET=sky
$ make TARGET=sky savetarget
$ make custom-sensing.upload TARGET=sky
```

After uploading a program into Contiki-NG, we try to monitor the serial output to see our custom sensor on Terminal:

```
$ make login TARGET=sky
```

You should see your reading values from ADC on Terminal.

Summary

We have reviewed some sensor and actuator devices. We also have learned how to work with sensing and actuating in Contiki-NG. Last, we developed a custom sensor to attach to a Contiki-NG mote through its expansion connector.

In the next chapter, we will learn how to build networking and communication in Contiki-NG. That is at the core of Contiki-NG's features.

CHAPTER 6

Networking

Contiki-NG comes with rich network-stack features to allow communication with others. In this chapter, we will explore the available network features on the Contiki-NG platform. Several scenarios will be provided to enable practice with implementing projects-based Contiki-NG, either in physical motes or in mote simulations.

The following is a list of topics that will be covered in this chapter:

- Networking in Contiki-NG
- Working with network simulation using COOJA
- IPv6 networking
- Routing on Contiki-NG
- IPv6 Multicast
- Working with Contiki-NG NullNet
- Working with a 6LoWPAN network
- Building a RESTful server for Contiki-NG

Networking in Contiki-NG

Contiki-NG still uses a traditional OSI (Open Systems Interconnection) stack to implement the Contiki-NG Network Protocol stack, called NETSTACK, to communicate among nodes. The Contiki-NG NETSTACK is shown in Figure 6-1. In this figure, we can see that the Contiki-NG NETSTACK implements four layers, as follows:

- Network layer (`NETSTACK_NETWORK`)
- MAC layer (`NETSTACK_MAC`)
- RDC (Radio Duty Cycling) layer (`NETSTACK_RDC`)
- Radio layer (`NETSTACK_RADIO`)

The Network layer (`NETSTACK_NETWORK`) in an OSI layer can be represented as Application, Transport, Network, Routing, and Adaptation. I will introduce each layer in the next section.

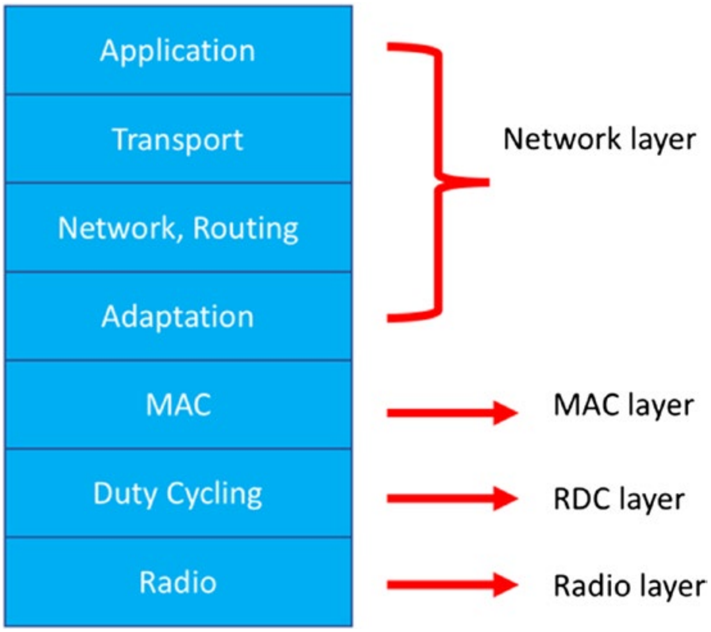


Figure 6-1. *Contiki-NG Network Protocol stack*

In NETSTACK implementation, Contiki-NG provides network libraries. You can find them in the `<contiki-ng>/os/net` folder. You can see this folder in Figure 6-2. The following is several code-sample implementations for Contiki-NG NETSTACK:

- Application layer: `http-socket.c`, `websocket.c`, `websocket-http-client.c`, and `mqtt.c`
- Transport: `udp-socket.c` and `tcp-socket.c`
- Network & Routing: `uip6.c` and `rpl.c`
- MAC: `mac.c` and `csma.c`

I recommend you review and learn the code for the Contiki-NG network stack, found in the `<contiki-ng>/os/net` folder. Thus, you will get more knowledge about how Network project builds Contiki-NG system.

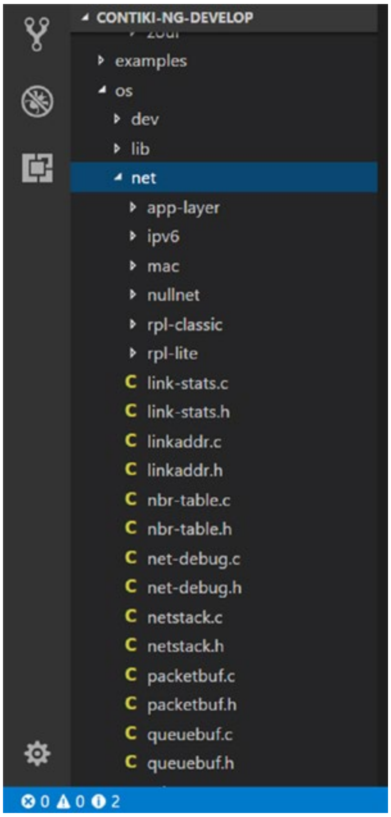


Figure 6-2. *NETSTACK code implementations in Contiki-NG*

Network Layer

Contiki-NG relies on an IPv6 stack. All TCP/UDP sockets in Contiki-NG use uIP (`uip.h` and `uip6.c` from `<contiki-ng>/os/net/ipv6`), which implements for IP, UDP, and TCP protocols in minimized models.

Currently, the network layer contains two sublayers, the upper IPv6 layer and the lower adaptation layer. These sublayers run on the top of IEEE 802.15.4 with Time-Slotted Channel Hopping (TSCH).

Regarding routing, Contiki-NG applies RPL (Routing Protocol for Low-power and Lossy Networks (LLNs)), which adopts the RFC standard, RFC 6550. RPL develops a routing graph from the root node or AP (Access Point).

If the routing graph has a form as cyclic graph and is built from a root node, it is called a DODAG (Destination Oriented Directed Acyclic Graph). A DODAG routing graph form can be seen in Figure 6-3.

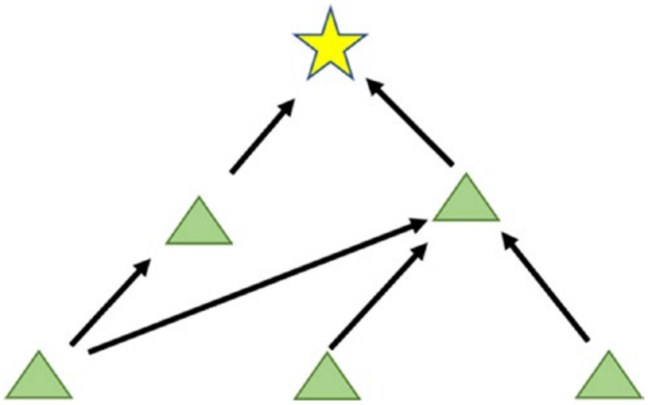


Figure 6-3. *DODAG routing graph form*

RPL routing in Contiki-NG supports three directions of traffic, as follows:

- Upward: from any node toward a root
- Downward: from the root to any node
- Any-to-any: flows among arbitrary pairs of nodes in the DODAG graph

For RPL implementation, Contiki-NG provides RPL classic and RPL lite. RPL classic is the original Contiki RPL implementation, called ContikiRPL. I recommend you read the ContikiRPL paper on this site: `http://www.diva-portal.org/smash/get/diva2:1042739/FULLTEXT01.pdf`.

You can find code implementations for both RPL classic and RPL lite in Contiki-NG. RPL classic can be found at `/net/rpl-classic` and RPL lite at `/net/rpl-lite` from the Contiki-NG code root. See them in Figure 6-4.

The `nullnet` library from Contiki-NG can be used to test your packet from upper to lower layers. This library can be found at `<contiki-ng>/os/net/nullnet`.

MAC Layer

The MAC layer is designed to address collisions in packet traffic and to apply back-off if there is traffic. Contiki-NG applies CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) for MAC layer implementation. Contiki-NG uses CSMA/CA on the IEEE 802.15.4 protocol. You can see program implementation in the `<contiki-ng>/os/net/mac` folder.

In the CSMA/CA algorithm, a mote will sense the medium before sending packets. If another mote is sending a packet, the mote will apply back-off with a certain value depending on the RDC layer. If the medium is free, the mote will send packets that have been prepared by the network layer.

Contiki-NG also provides `nullmac` for testing that is a part of `nullnet` from the network layer. `nullmac` will forward packets from the upper layer to the radio driver and vice versa.

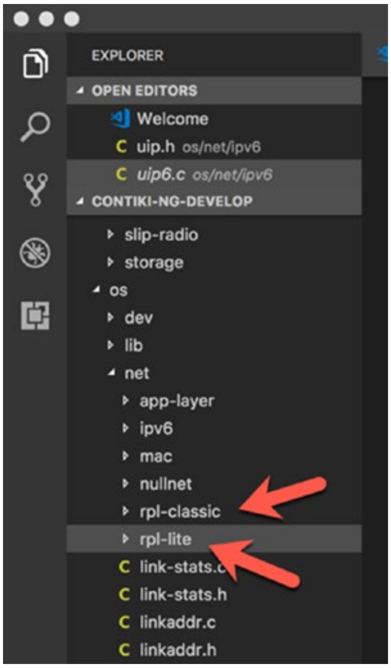


Figure 6-4. *RPL classic and lite libraries in Contiki-NG*

RDC Layer

The Radio Duty Cycling (RDC) layer saves energy by allowing a node to keep its radio transceiver off most of the time. Contiki-NG supports the ContikiMAC protocol based on the principles behind low-power listening. ContikiMAC uses Time Slotted Channel Hopping (TSCH) that is a part of the MAC layer of the IEEE 802.15.4e-2012 amendment.

Radio Layer

The radio layer is the lowest layer in the Contiki-NG NETSTACK. The radio layer is handled by radio module from the Contiki-NG mote. Most radio layers work on the IEEE 802.15.4 protocol mechanism.

Network Simulation Using COOJA

In Chapter 1, we learned how to work with COOJA to build a Contiki-NG simulation. In this section, we will continue to apply COOJA to create a network simulation. For this simple demo, we will use the same scenario as in Chapter 4. We will perform broadcasting among Contiki-NG motes.

To implement the demo, we will perform the following tasks:

- Create a simulation project.
- Add a UDP server mote.
- Add UDP client motes.
- Run the simulation.

Each task will be performed in the following sections.

Creating Simulation Project

The first step is to create a simulation project using COOJA. From your platform Terminal, you can run the COOJA tool. For instance, I run it from Ubuntu Linux. You can type these commands:

```
$ cd contiki-ng/tools/cooja
$ sudo ant run
```

After it has executed, you should get the COOJA application that is shown in Figure 6-5.

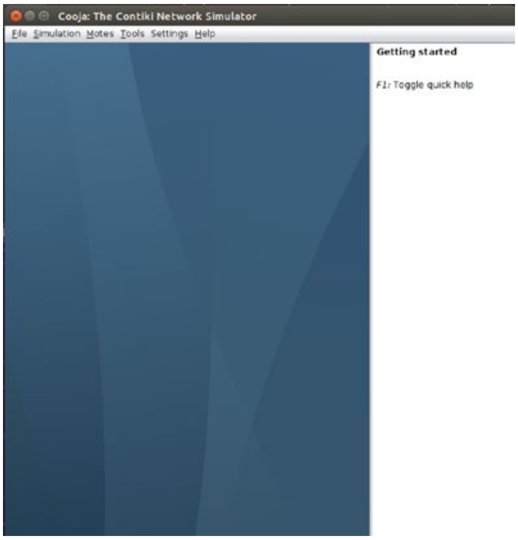

Cooja: The Contiki Network Simulator
File Simulation Motes Tools Settings Help
Getting started
F1: Toggle quick help

Figure 6-5. *COOJA application*

To start a new simulation, you can click File ➤ New simulation, shown in Figure 6-6.

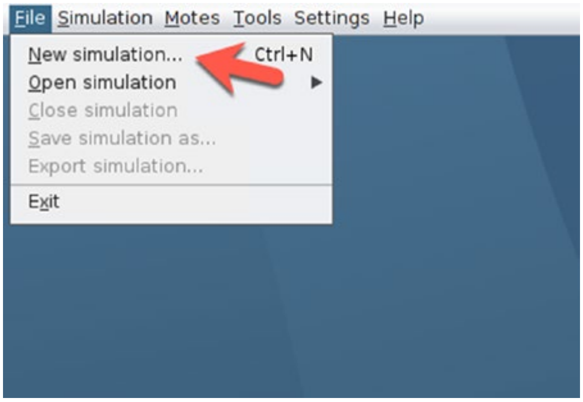
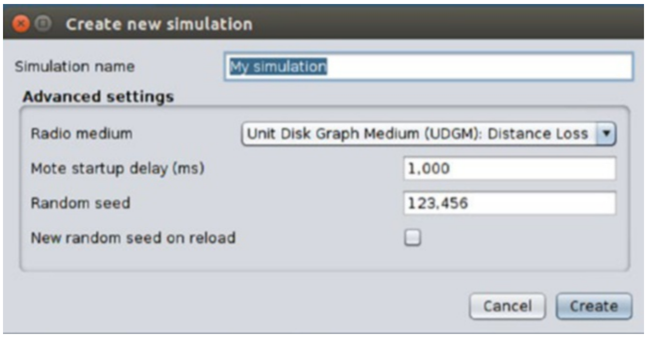


Figure 6-6. *Create a new simulation in COOJA*

Then, you should get the dialog that is shown in Figure 6-7. Fill in the simulation name with default settings on the Advanced Settings panel. For instance, I fill in the simulation name with `My simulation`.



Simulation name: My simulation

Radio medium: Unit Disk Graph Medium (UDGM): Distance Loss

Mote startup delay (ms): 1,000

Random seed: 123,456

New random seed on reload: ☐

Figure 6-7. *Fill in simulation name and other settings*

If done, you can click the Create button to create the simulation.

After that, COOJA will create a new simulation for you. Figure 6-8 shows a simulation dashboard from COOJA. Now you are ready to configure the simulation.

In the next section, we will add a UDP server mote to our simulation.

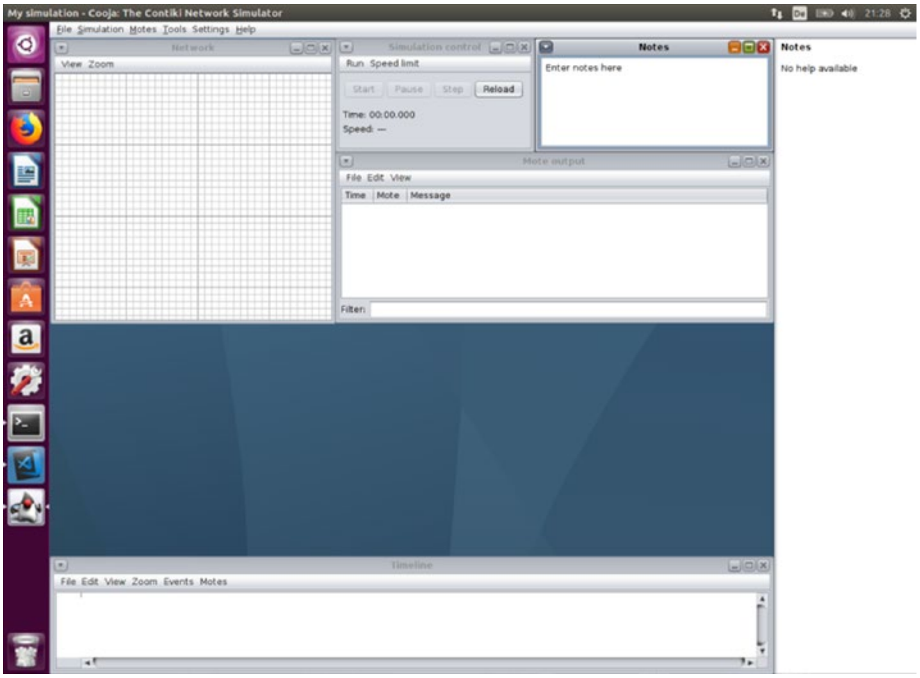


Figure 6-8. *Cooja with simulation dashboard*

Adding UDP Server Mote

In this section, we will add a mote as the UDP server. This mote will listen to incoming messages. Once a message is received from a client, the UDP server will reply by sending that message. For the demo, we will use a mote with the Sky platform type.

To add a new mote on COOJA, go to Add Motes ➤ Create a mote type ➤ Sky mote. You can see this menu in Figure 6-9.

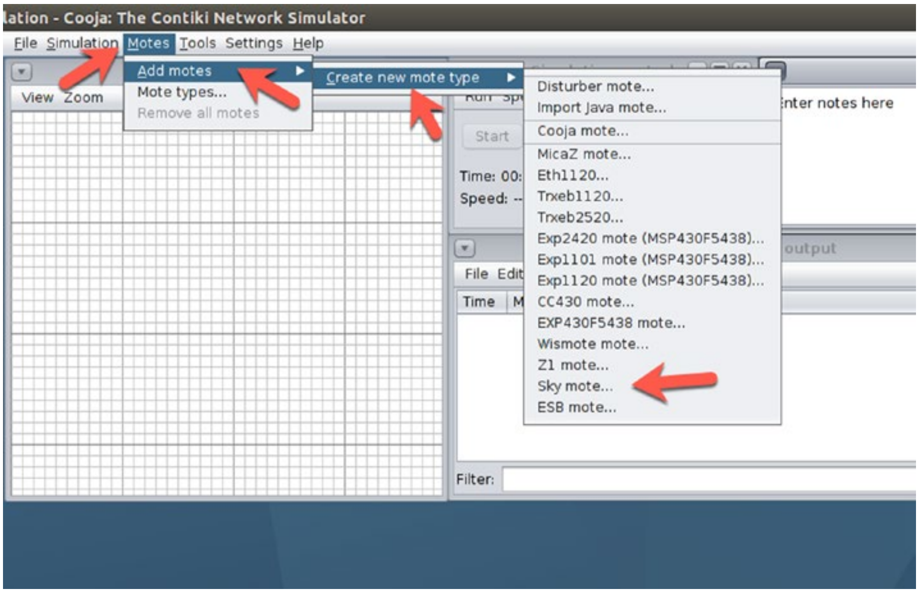
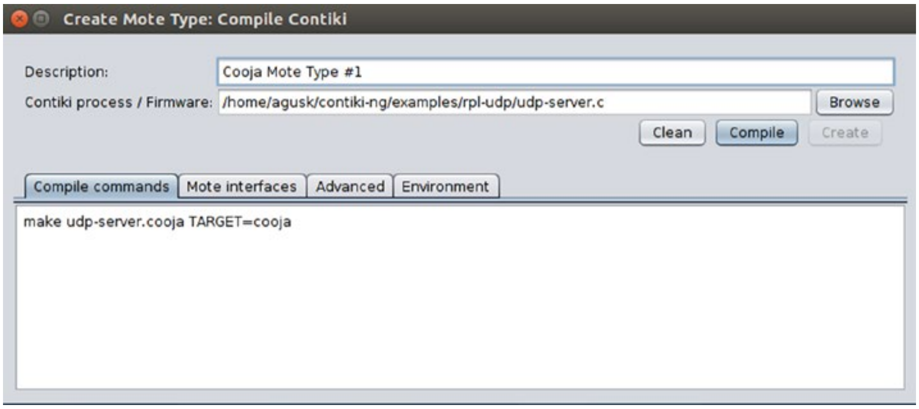


***Figure 6-9.** Adding a new mote*

You will get the dialog shown in Figure 6-10. You can fill in the description of the mote. Then, set the Contiki firmware from the UDP server, `udp-server.c`. You can find `udp-server.c` in the `<contiki-ng>/examples/rpl-udp/` folder. Click the Browse button and navigate to the `udp-server.c` file.



Create Mote Type: Compile Contiki

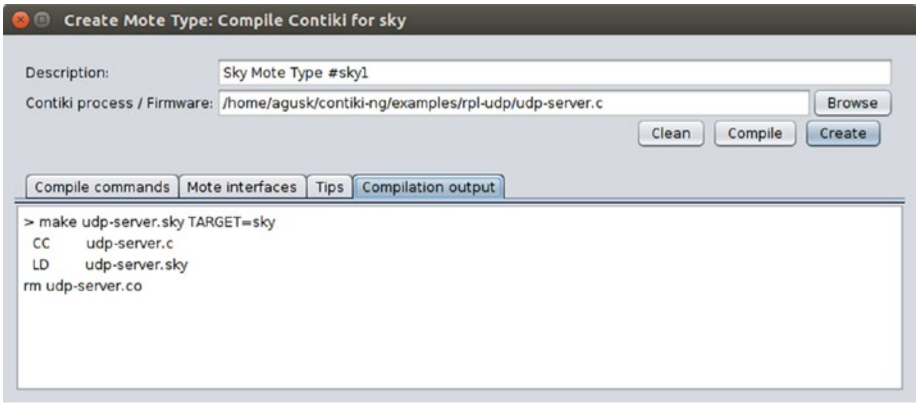
Description: Cooja Mote Type #1

Contiki process / Firmware: /home/agusk/contiki-ng/examples/rpl-udp/udp-server.c

```
make udp-server.cooja TARGET=cooja
```

***Figure 6-10.** Add the UDP server mote*

After selecting the `udp-server.c` file, you can compile this file to ensure there are no errors in the program. Click the Compile button to compile the program. If it succeeds, you should see the successful compilation on the Compilation Output tab, shown in Figure 6-11.



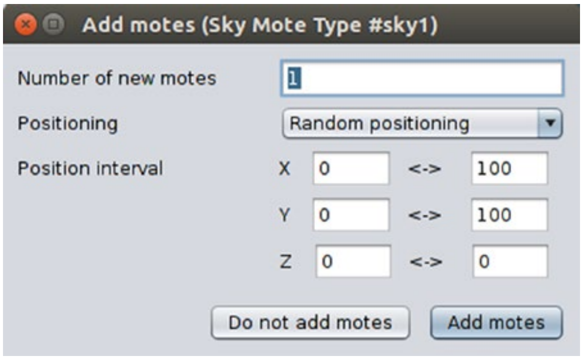
Description: Sky Mote Type #sky1

Contiki process / Firmware: /home/agusk/contiki-ng/examples/rpl-udp/udp-server.c

```
> make udp-server.sky TARGET=sky
  CC       udp-server.c
  LD       udp-server.sky
rm udp-server.co
```

***Figure 6-11.** Compile the UDP server mote*

If you have compiled the program, you can click the Create button. Then, you should get the dialog that is shown in Figure 6-12.



Number of new motes: 1

Positioning: Random positioning

Position interval: X 0 <-> 100; Y 0 <-> 100; Z 0 <-> 0

***Figure 6-12.** Configure the mote number and its position*

In this scenario, we only add one mote for the UDP server. You can fill in `1` for the "Number of new motes" field and select `Random positioning` for the "Positioning" dropdown.

If done, you can click the Add Motes button. You should see this mote on the Network panel in the simulation dashboard. You can see it in Figure 6-13.

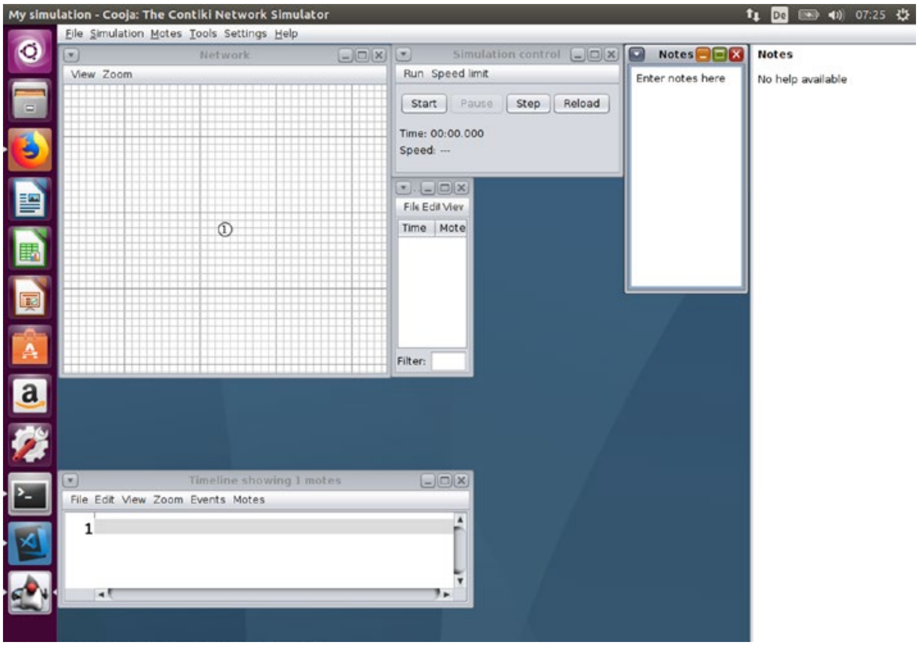


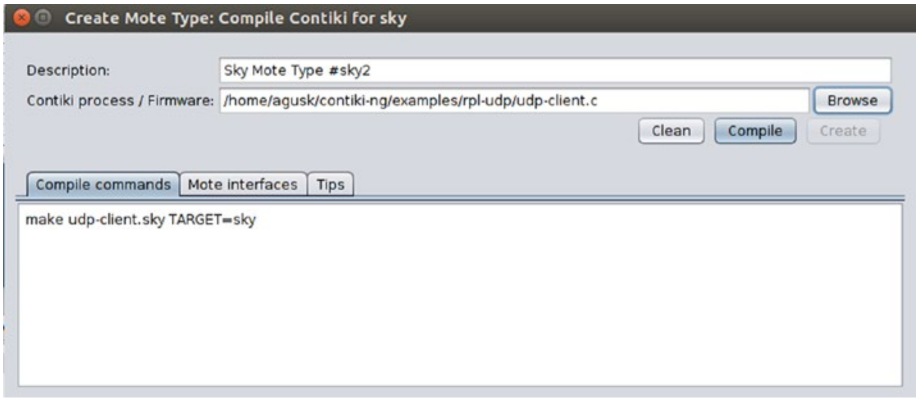
Figure 6-13. *UDP server is deployed on COOJA*

Next, we will add some motes for the UDP client. We will perform this task in the next section.

Adding UDP Client Motes

After we have created one UDP server mote, we can create some UDP client motes. For this demo, we will add five motes. To add a new mote, you perform this task as in the previous section.

For a UDP client mote, you can put `udp-client.c` as the Contiki firmware. You can find it in the `<contiki-ng>/examples/rpl-udp/` folder. You can see the UDP client program in Figure 6-14.

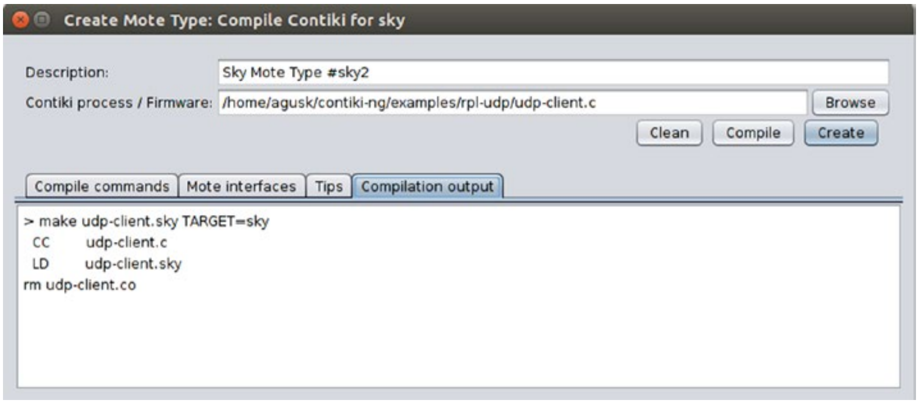


Description: Sky Mote Type #sky2
Contiki process / Firmware: /home/agusk/contiki-ng/examples/rpl-udp/udp-client.c

```
make udp-client.sky TARGET=sky
```

Figure 6-14. *Adding UDP client mote*

Then, you should compile the UDP client firmware to ensure there are no errors in the program. You can click the Compile button. You can see my successful compilation from the UDP client in Figure 6-15.

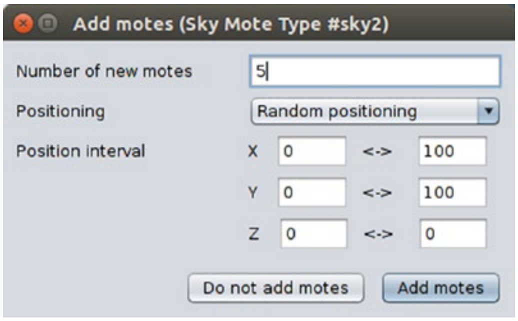


Description: Sky Mote Type #sky2
Contiki process / Firmware: /home/agusk/contiki-ng/examples/rpl-udp/udp-client.c

```
> make udp-client.sky TARGET=sky
  CC        udp-client.c
  LD        udp-client.sky
rm udp-client.co
```

Figure 6-15. *Compiling UDP client mote*

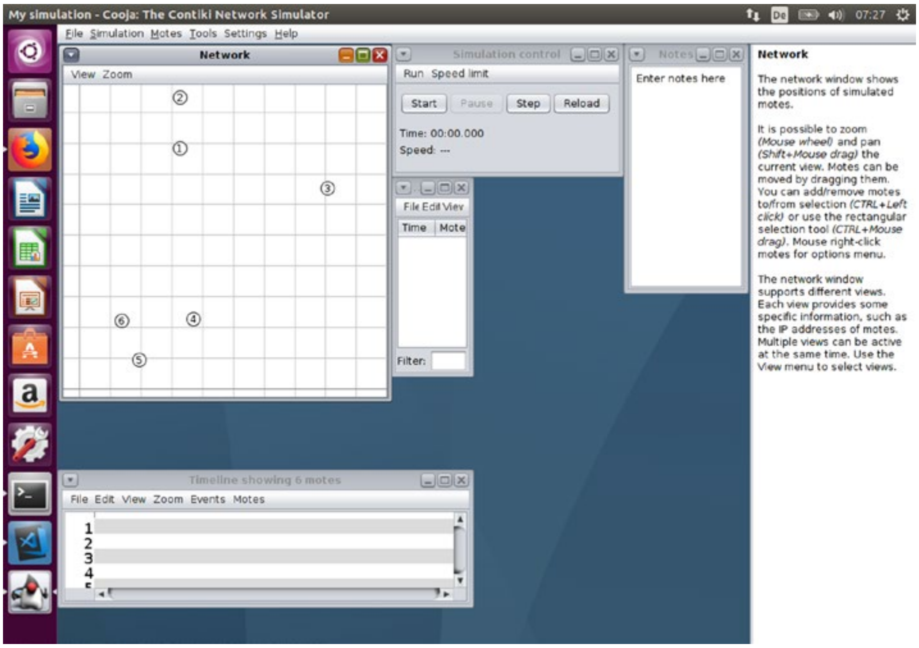
You can add motes to the Network panel by clicking the Create button in the dialog shown in Figure 6-15. After clicking, you should get the dialog that is shown in Figure 6-16. For this demo, fill in 5 in the "Number of new motes" field. All fields are default values.



Number of new motes: 5
Positioning: Random positioning
Position interval: X 0 <-> 100
Y 0 <-> 100
Z 0 <-> 0

Figure 6-16. *Adding five UDP client motes*

After filling in the number of motes, you can click the Add Motes button. Then, you should see five UDP client motes in the Network panel in the simulation dashboard. Now you have six motes in the simulation, shown in Figure 6-17.



Time: 00:00.000
Speed: ---

Network

The network window shows the positions of simulated motes.

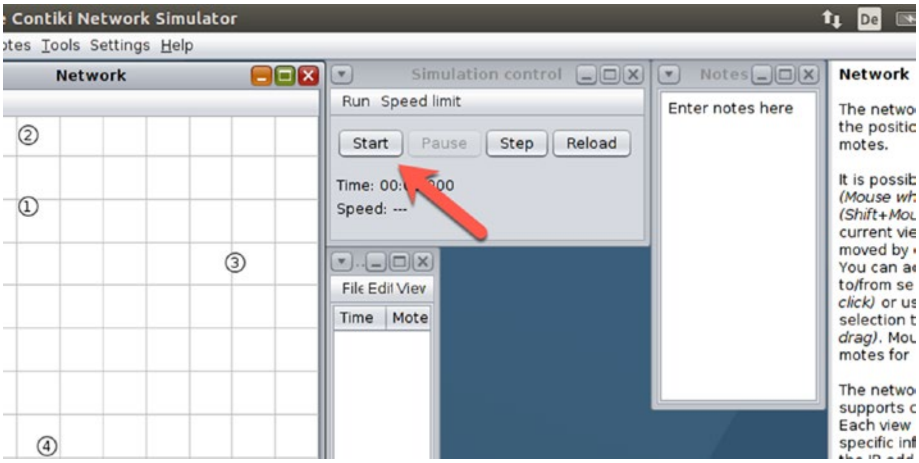
It is possible to zoom (*Mouse wheel*) and pan (*Shift+Mouse drag*) the current view. Motes can be moved by dragging them. You can add/remove motes to/from selection (*CTRL+Left click*) or use the rectangular selection tool (*CTRL+Mouse drag*). Mouse right-click motes for options menu.

The network window supports different views. Each view provides some specific information, such as the IP addresses of motes. Multiple views can be active at the same time. Use the View menu to select views.

Figure 6-17. *Deployed UDP client motes on COOJA*

Running a Simulation

Once we have added the UDP server and client motes into the COOJA simulation, we can run the simulation. To do so, click the Start button on the Simulation Control dialog, as shown in Figure 6-18. If you don't see this dialog, you can open it by going to Simulation ➤ Control panel.



Network

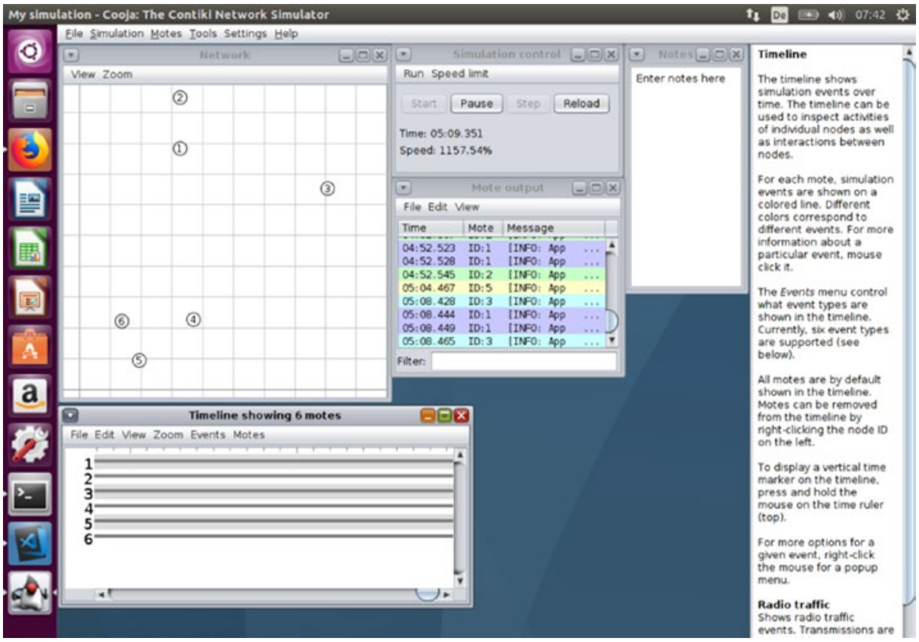
The netwo
the positic
motes.

It is possib
(Mouse wh
(Shift+Mou
current vie
moved by
You can ad
to/from se
click) or us
selection t
drag). Mou
motes for

The netwo
supports c
Each view
specific inf

Figure 6-18. *Starting a simulation*

After clicking the Start button, you should see the packet network and graphic simulation on COOJA. You can see it in Figure 6-19.



Time: 05:09.351
Speed: 1157.54%

```
Time       Mote  Message
04:52.523  ID:1  [INFO: App  ...
04:52.528  ID:1  [INFO: App  ...
04:52.545  ID:2  [INFO: App  ...
05:04.467  ID:5  [INFO: App  ...
05:08.428  ID:3  [INFO: App  ...
05:08.444  ID:1  [INFO: App  ...
05:08.449  ID:1  [INFO: App  ...
05:08.465  ID:3  [INFO: App  ...
```

Timeline

The timeline shows simulation events over time. The timeline can be used to inspect activities of individual nodes as well as interactions between nodes.

For each mote, simulation events are shown on a colored line. Different colors correspond to different events. For more information about a particular event, mouse click it.

The *Events* menu control what event types are shown in the timeline. Currently, six event types are supported (see below).

All motes are by default shown in the timeline. Motes can be removed from the timeline by right-clicking the node ID on the left.

To display a vertical time marker on the timeline, press and hold the mouse on the time ruler (top).

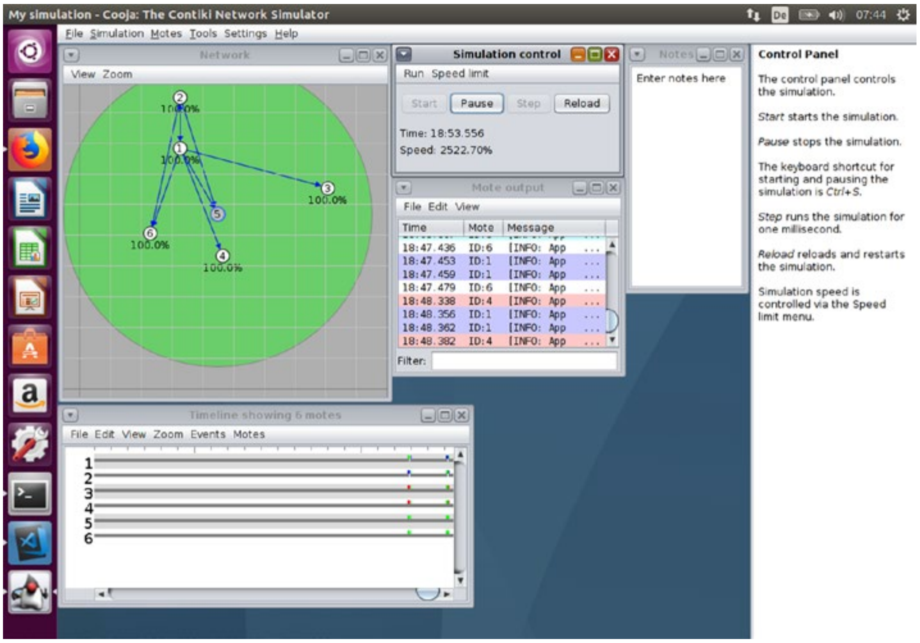
For more options for a given event, right-click the mouse for a popup menu.

Radio traffic
Shows radio traffic events. Transmissions are

Figure 6-19. *A simulation is running on COOJA*

If the distance between motes is far, some motes probably won't connect or receive UDP messages. You can change the mote location so each mote can be connected.

Now you can run the simulation again. You should see a graphic simulation on COOJA. A sample of the simulation can be seen in Figure 6-20.



Time: 18:53.556
Speed: 2522.70%

```
Time        Mote   Message
18:47.436   ID:6   [INFO: App   ...
18:47.453   ID:1   [INFO: App   ...
18:47.459   ID:1   [INFO: App   ...
18:47.479   ID:6   [INFO: App   ...
18:48.338   ID:4   [INFO: App   ...
18:48.356   ID:1   [INFO: App   ...
18:48.362   ID:1   [INFO: App   ...
18:48.382   ID:4   [INFO: App   ...
```

Control Panel

The control panel controls the simulation.

Start starts the simulation.

Pause stops the simulation.

The keyboard shortcut for starting and pausing the simulation is *Ctrl+S*.

Step runs the simulation for one millisecond.

Reload reloads and restarts the simulation.

Simulation speed is controlled via the Speed limit menu.

Figure 6-20. *Changing mote location*

IPv6 Networking

IPv6 (Internet Protocol Version 6) is the Internet's next-generation protocol, designed to replace the current protocol, IP Version 4 (IPv4). Most network systems still use IPv4 to communicate with other systems. Sample IP addresses from IPv4 and IPv6 are shown here:

```
// IPv4
192.168.0.2
// IPv6
2021:db8:ffff:1:201:02ff:fe03:0415
```

To test whether your network uses IPv4, IPv6, or both, you use a browser and navigate to http://test-ipv6.com. Based on IPv6 and IPv4 statistics from http://ipv6-test.com/stats/, IPv6 penetration in the market still does not dominate. Figure 6-21 shows a comparison of protocol support for IPv6 and IPv4. For instance, on July 2017, IPv6-only dominates at about 54.7 percent.

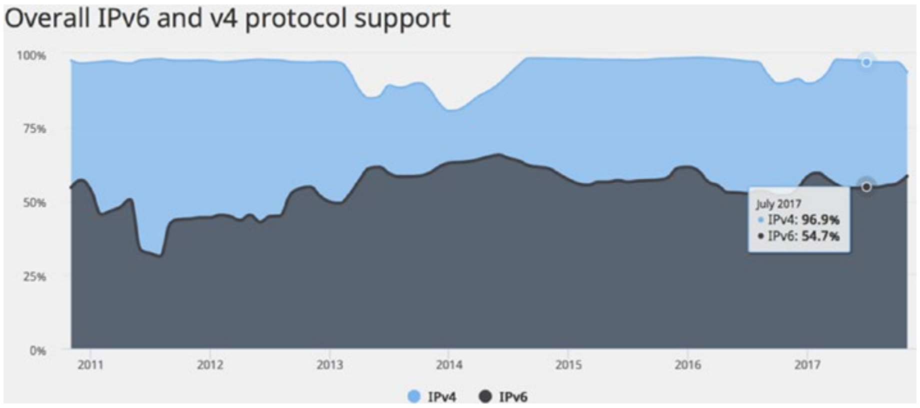


Figure 6-21. *Comparing IPv4 and IPv6 protocol support worldwide*

For more learning material about IPv6, I recommend you read some textbooks or technical articles related to IPv6 technology. This book does not cover IPv6 technology in any depth.

Contiki-NG can work with an IPv6 network by default. Contiki-NG projects provide uIP as the network stack implementation for IP, UDP, and TCP protocols included in the basic ICMP protocol. The uIP library can run on constrained devices, such as Tmote Sky/TelosB, TI cc26xx/cc13xx, Firefly, RE-mote, and Orion.

For our IPv6 demo on Contiki-NG, we can perform testing using a Contiki-NG shell (NG shell). To enable an NG shell for your program, you should add a shell module to your `Makefile` file:

```
MODULES += os/services/shell
```

Then, you can compile and upload to your mote. Since the shell module needs more space, you should use a mote platform that can handle NG shell spaces. In this demo, I use a TI CC2650 LaunchPad board.

For testing, we need two motes at least. Upload your project; for instance, hello-world with NG shell enabled. After uploading Contiki-NG firmware onto the boards, we can remote into the NG shell from a serial terminal.

For instance, I remote into the TI CC2650 LaunchPad via the `/dev/ttyACM0` port:

```
$ make TARGET=srf06-cc26xx BOARD=launchpad/cc2650 login PORT=/
dev/ttyACM0
```

Open a new Terminal window. Then, perform a serial remote on the second mote. For instance, my second mote runs on the `/dev/ttyACM2` port:

```
$ make TARGET=srf06-cc26xx BOARD=launchpad/cc2650 login PORT=/
dev/ttyACM2
```

After connecting to the NG shell, we can perform some tests related to IPv6 operations. You can check the current IPv6 address on each mote. You can type this command in the NG shell:

```
> ip-addr
```

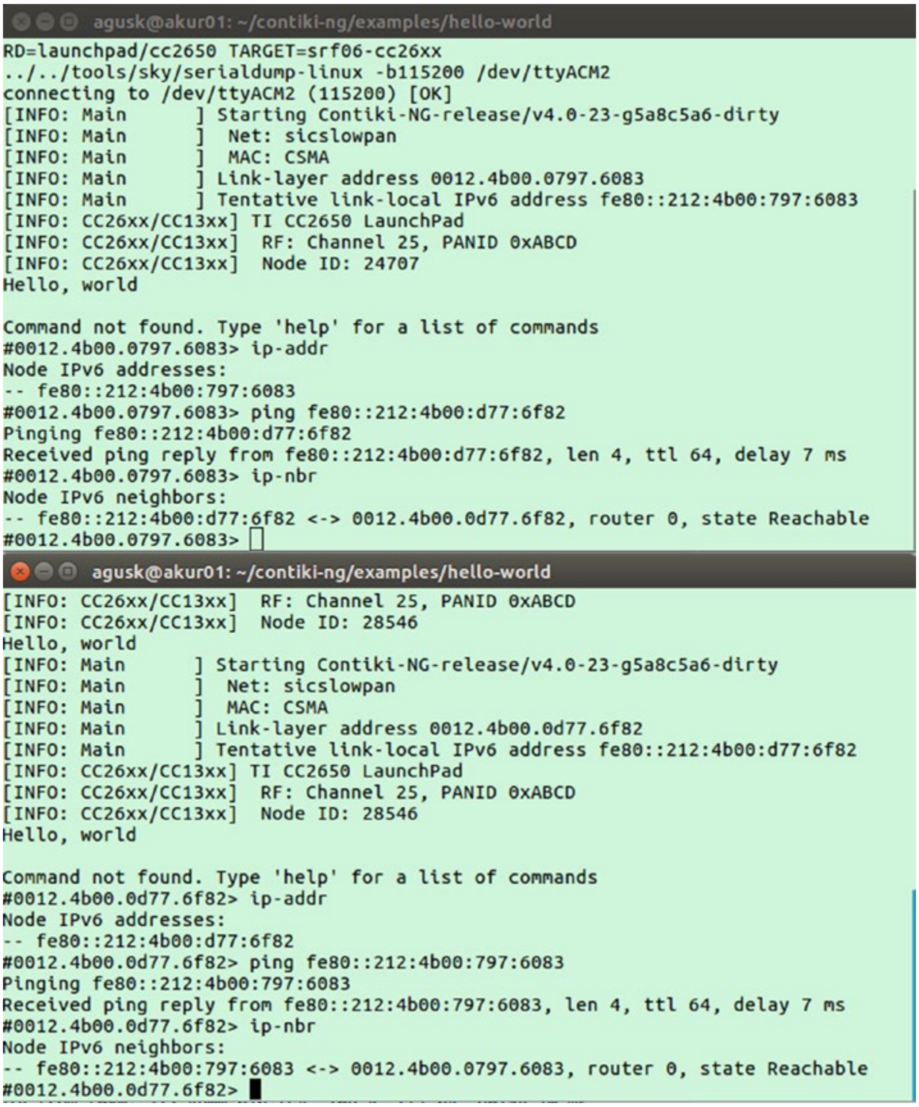
You should see an IPv6 address for each mote. Next, you can perform a ping to one of the motes. For instance, I perform a ping on a mote with the IPv6 address `fe80::212:4b00:d77:6f82`:

```
> ping fe80::212:4b00:d77:6f82
```

You should get a response from ping operations. Last, our mote can discover its neighbor. By default, Contiki-NG enables `UIP_ND6_AUTOFILL_NBR_CACHE` to be discoverable. You can perform this command to discover a mote's neighbor:

```
> ip-nbr
```

All these operations can be seen in Figure 6-22.



```
agusk@akur01: ~/contiki-ng/examples/hello-world
RD=launchpad/cc2650 TARGET=srf06-cc26xx
../../tools/sky/serialdump-linux -b115200 /dev/ttyACM2
connecting to /dev/ttyACM2 (115200) [OK]
[INFO: Main      ] Starting Contiki-NG-release/v4.0-23-g5a8c5a6-dirty
[INFO: Main      ]  Net: sicslowpan
[INFO: Main      ]  MAC: CSMA
[INFO: Main      ] Link-layer address 0012.4b00.0797.6083
[INFO: Main      ] Tentative link-local IPv6 address fe80::212:4b00:797:6083
[INFO: CC26xx/CC13xx] TI CC2650 LaunchPad
[INFO: CC26xx/CC13xx]  RF: Channel 25, PANID 0xABCD
[INFO: CC26xx/CC13xx]  Node ID: 24707
Hello, world

Command not found. Type 'help' for a list of commands
#0012.4b00.0797.6083> ip-addr
Node IPv6 addresses:
-- fe80::212:4b00:797:6083
#0012.4b00.0797.6083> ping fe80::212:4b00:d77:6f82
Pinging fe80::212:4b00:d77:6f82
Received ping reply from fe80::212:4b00:d77:6f82, len 4, ttl 64, delay 7 ms
#0012.4b00.0797.6083> ip-nbr
Node IPv6 neighbors:
-- fe80::212:4b00:d77:6f82 <-> 0012.4b00.0d77.6f82, router 0, state Reachable
#0012.4b00.0797.6083>
```

```
agusk@akur01: ~/contiki-ng/examples/hello-world
[INFO: CC26xx/CC13xx]  RF: Channel 25, PANID 0xABCD
[INFO: CC26xx/CC13xx]  Node ID: 28546
Hello, world
[INFO: Main      ] Starting Contiki-NG-release/v4.0-23-g5a8c5a6-dirty
[INFO: Main      ]  Net: sicslowpan
[INFO: Main      ]  MAC: CSMA
[INFO: Main      ] Link-layer address 0012.4b00.0d77.6f82
[INFO: Main      ] Tentative link-local IPv6 address fe80::212:4b00:d77:6f82
[INFO: CC26xx/CC13xx] TI CC2650 LaunchPad
[INFO: CC26xx/CC13xx]  RF: Channel 25, PANID 0xABCD
[INFO: CC26xx/CC13xx]  Node ID: 28546
Hello, world

Command not found. Type 'help' for a list of commands
#0012.4b00.0d77.6f82> ip-addr
Node IPv6 addresses:
-- fe80::212:4b00:d77:6f82
#0012.4b00.0d77.6f82> ping fe80::212:4b00:797:6083
Pinging fe80::212:4b00:797:6083
Received ping reply from fe80::212:4b00:797:6083, len 4, ttl 64, delay 7 ms
#0012.4b00.0d77.6f82> ip-nbr
Node IPv6 neighbors:
-- fe80::212:4b00:797:6083 <-> 0012.4b00.0797.6083, router 0, state Reachable
#0012.4b00.0d77.6f82>
```

Figure 6-22. *IPv6 testing via Contiki-NG shell*

Routing on Contiki-NG

Routing is the process of moving packets across a network from source to destination. This process is usually performed by dedicated network devices, such as routers and computers. Routing is a key feature of the Internet. Routing topics as a research area is still popular. Some researchers propose algorithms to address routing problems. In this section, we will review routing and how to implement it in the Contiki-NG platform.

Introducing Basic Routing

We already know that routing is applied to address how the packet is delivered from one point to another. Consider the paths depicted in Figure 6-23. For instance, we want to send a packet from A to D. Which path do you want to take?

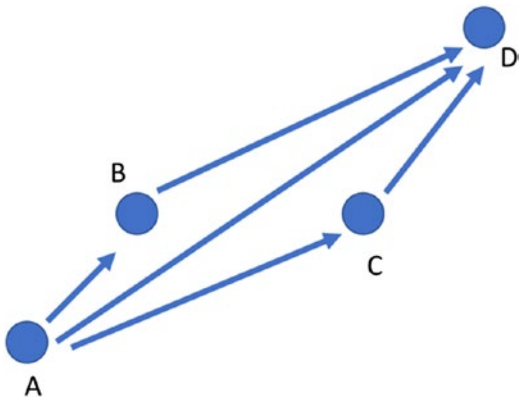


Figure 6-23. *Data network flow on some motes*

Figure 6-23 shows a number of path options to send a packet from A to D. We can take one of three path options: A-B-D, A-D, and A-C-D. Which one is the best path? This is a challenge.

When selecting a path, you must consider what your goal is and what your success criteria are. We can define a cost for each path. Then, we can select the best path with the lowest cost. Battery usage can be one of the cost parameters when you want to perform a certain routing algorithm.

That is one routing issue. Unfortunately, this book does not focus on routing algorithms. I recommend you read about routing topics in textbooks or technical articles. We will use the current routing algorithms that are applied in Contiki-NG.

Single-Hop and Multi-Hop Networking

When a packet is transferred from the source to the final destination, it probably goes through a number of network devices. In networking, we will find a term called a *hop. Hop* is a term used to describe the different network devices a packet has to go through to reach its final destination point.

We can categorize networking models by the number of hops, such as single-hop and multi-hop networks. To better understand these network models, see the network topology depicted in Figure 6-24. A single-hop network would be pointed to the A-D path. The packet is sent from A to D through a single router.

Multi-hop networks send a packet through two or more networks to reach its final destination address. From Figure 6-24, we can see that the E-F path is considered a multi-hop network.

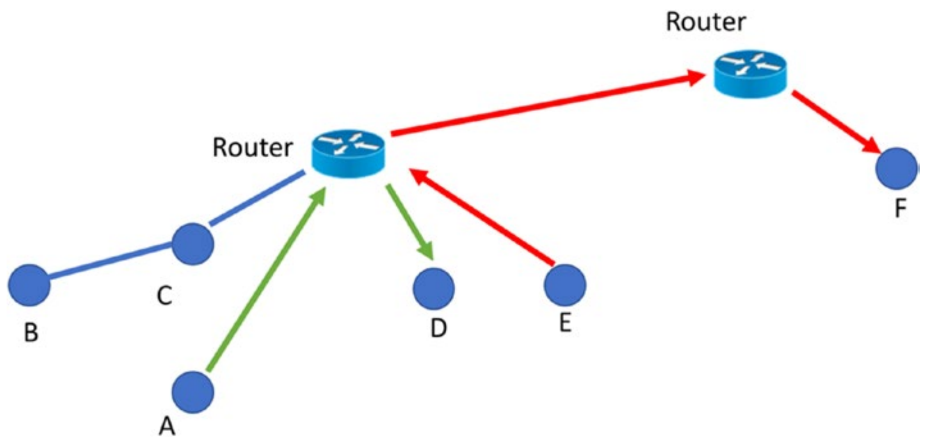


Figure 6-24. *A network topology*

The Contiki-NG platform supports both single-hop and multi-hop networks. Depending on your network design, your Contiki-NG program should be aware of single-hop and multi-hop networks.

Routing on Contiki-NG

Currently, Contiki-NG supports two RPL routing methods: RPL classic and RPL lite. RPL classic is the original Contiki's RPL implementation, called ContikiRPL. If you want to read further about ContikiRPL, I recommend you read this paper: `http://www.diva-portal.org/smash/get/diva2:1042739/FULLTEXT01.pdf`. Otherwise, Contiki-NG applies RPL lite for default RPL implementation.

Since Contiki-NG applies RPL lite by default, we test RPL. For instance, we have two motes for testing. Enable NG shell on your program. You can use the hello-world program with NG shell enabled. Flash this program to all motes.

Now you can access the Contiki-NG motes via NG shell. First, test an RPL root on the first mote. You can type this command:

```
> rpl-set-root 1
```

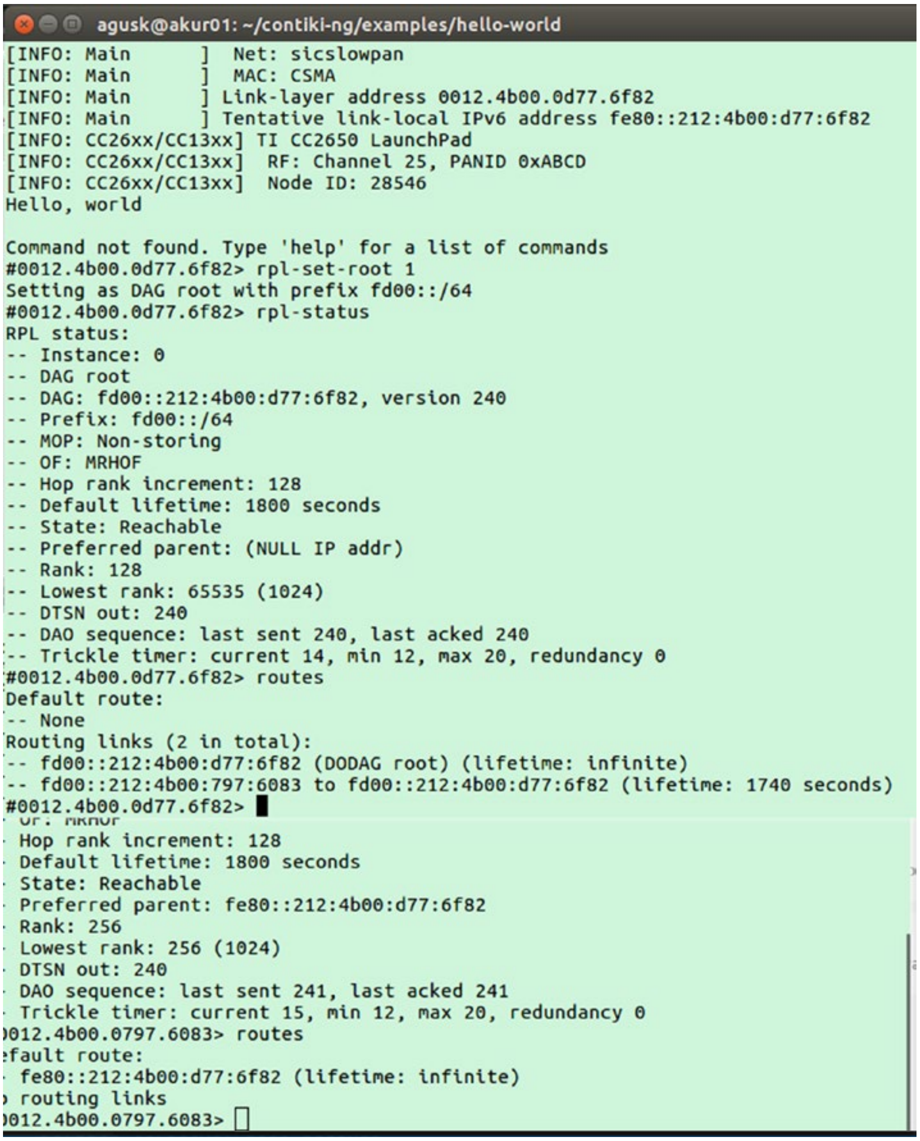
Then, you can check the RPL status using this command:

```
> rpl-status
```

You also can check the RPL route table that is applied on this mote. Type this command:

```
> routes
```

You can see my program output that has performed those tasks in Figure 6-25.



agusk@akur01: ~/contiki-ng/examples/hello-world

```
[INFO: Main      ]  Net: sicslowpan
[INFO: Main      ]  MAC: CSMA
[INFO: Main      ] Link-layer address 0012.4b00.0d77.6f82
[INFO: Main      ] Tentative link-local IPv6 address fe80::212:4b00:d77:6f82
[INFO: CC26xx/CC13xx] TI CC2650 LaunchPad
[INFO: CC26xx/CC13xx]  RF: Channel 25, PANID 0xABCD
[INFO: CC26xx/CC13xx]  Node ID: 28546
Hello, world

Command not found. Type 'help' for a list of commands
#0012.4b00.0d77.6f82> rpl-set-root 1
Setting as DAG root with prefix fd00::/64
#0012.4b00.0d77.6f82> rpl-status
RPL status:
-- Instance: 0
-- DAG root
-- DAG: fd00::212:4b00:d77:6f82, version 240
-- Prefix: fd00::/64
-- MOP: Non-storing
-- OF: MRHOF
-- Hop rank increment: 128
-- Default lifetime: 1800 seconds
-- State: Reachable
-- Preferred parent: (NULL IP addr)
-- Rank: 128
-- Lowest rank: 65535 (1024)
-- DTSN out: 240
-- DAO sequence: last sent 240, last acked 240
-- Trickle timer: current 14, min 12, max 20, redundancy 0
#0012.4b00.0d77.6f82> routes
Default route:
-- None
Routing links (2 in total):
-- fd00::212:4b00:d77:6f82 (DODAG root) (lifetime: infinite)
-- fd00::212:4b00:797:6083 to fd00::212:4b00:d77:6f82 (lifetime: 1740 seconds)
#0012.4b00.0d77.6f82>
```

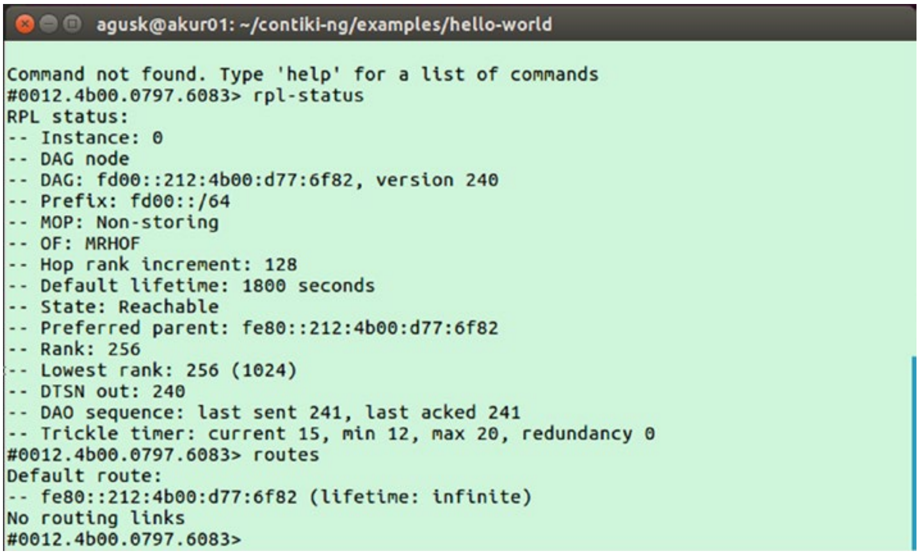
```
 Hop rank increment: 128
 Default lifetime: 1800 seconds
 State: Reachable
 Preferred parent: fe80::212:4b00:d77:6f82
 Rank: 256
 Lowest rank: 256 (1024)
 DTSN out: 240
 DAO sequence: last sent 241, last acked 241
 Trickle timer: current 15, min 12, max 20, redundancy 0
)012.4b00.0797.6083> routes
efault route:
 fe80::212:4b00:d77:6f82 (lifetime: infinite)
 routing links
)012.4b00.0797.6083>
```

Figure 6-25. *RPL operations on the first mote*

Next, you also can check the RPL status and its routes on another mote. You can type these commands in the NG shell:

```
> rpl-status
> routes
```

A sample of the program output is shown in Figure 6-26.



```
agusk@akur01: ~/contiki-ng/examples/hello-world
Command not found. Type 'help' for a list of commands
#0012.4b00.0797.6083> rpl-status
RPL status:
-- Instance: 0
-- DAG node
-- DAG: fd00::212:4b00:d77:6f82, version 240
-- Prefix: fd00::/64
-- MOP: Non-storing
-- OF: MRHOF
-- Hop rank increment: 128
-- Default lifetime: 1800 seconds
-- State: Reachable
-- Preferred parent: fe80::212:4b00:d77:6f82
-- Rank: 256
-- Lowest rank: 256 (1024)
-- DTSN out: 240
-- DAO sequence: last sent 241, last acked 241
-- Trickle timer: current 15, min 12, max 20, redundancy 0
#0012.4b00.0797.6083> routes
Default route:
-- fe80::212:4b00:d77:6f82 (lifetime: infinite)
No routing links
#0012.4b00.0797.6083>
```

Figure 6-26. *RPL operations on the second mote*

IPv6 Multicast

We can categorize data communication based on how the data is transferred. There are three models in data communication: unicast, broadcast, and multicast.

Unicast describes communication where a piece of information is sent from one point to another point. In the Unicast model, there is one sender and one receiver. Network protocols–based TCP transport such as http, smtp, ftp, and telnet support the unicast transfer mode.

Broadcast is a communication model where a piece of information is sent from one point to all other points. In this model, there is still one sender, but the information is sent to all connected receivers. There may be no receivers. ARP (Address Resolution Protocol) uses broadcast to send an address resolution query to all computers.

Multicast describes communication where a piece of information is sent from one or more points to a set of other points. In this model, there may be one or more senders. The information is distributed to a number of receivers.

The main difference between multicast and broadcast is to provide opt-in option for receivers. The receiver that wants to receive data should register to gain access to the sender. This registration will inform the network that you are interested and have opted in to receiving data. Otherwise, the receiver never receives the data. To compare how unicast, broadcast, and multicast send packets, see Figure 6-27.

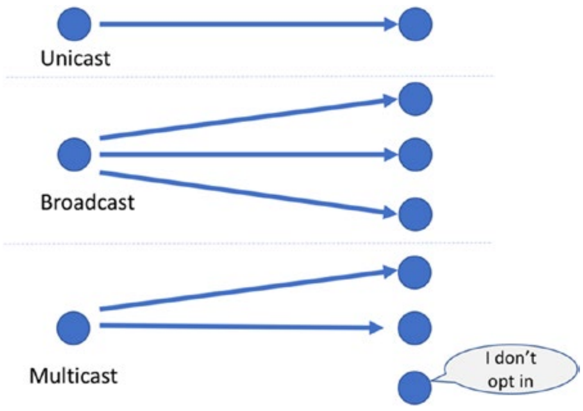


Figure 6-27. *Unicast, broadcast, and multicast*

To work with IPv6 multicast in a Contiki-NG project, you should add the multicast module to your project. You can add this script in the `Makefile` file:

```
MODULES += os/net/ipv6/multicast
```

We also activate RPL classic routing on the Contiki-NG project. You can add this script into the Makefile file:

```
MAKE_ROUTING = MAKE_ROUTING_RPL_CLASSIC
```

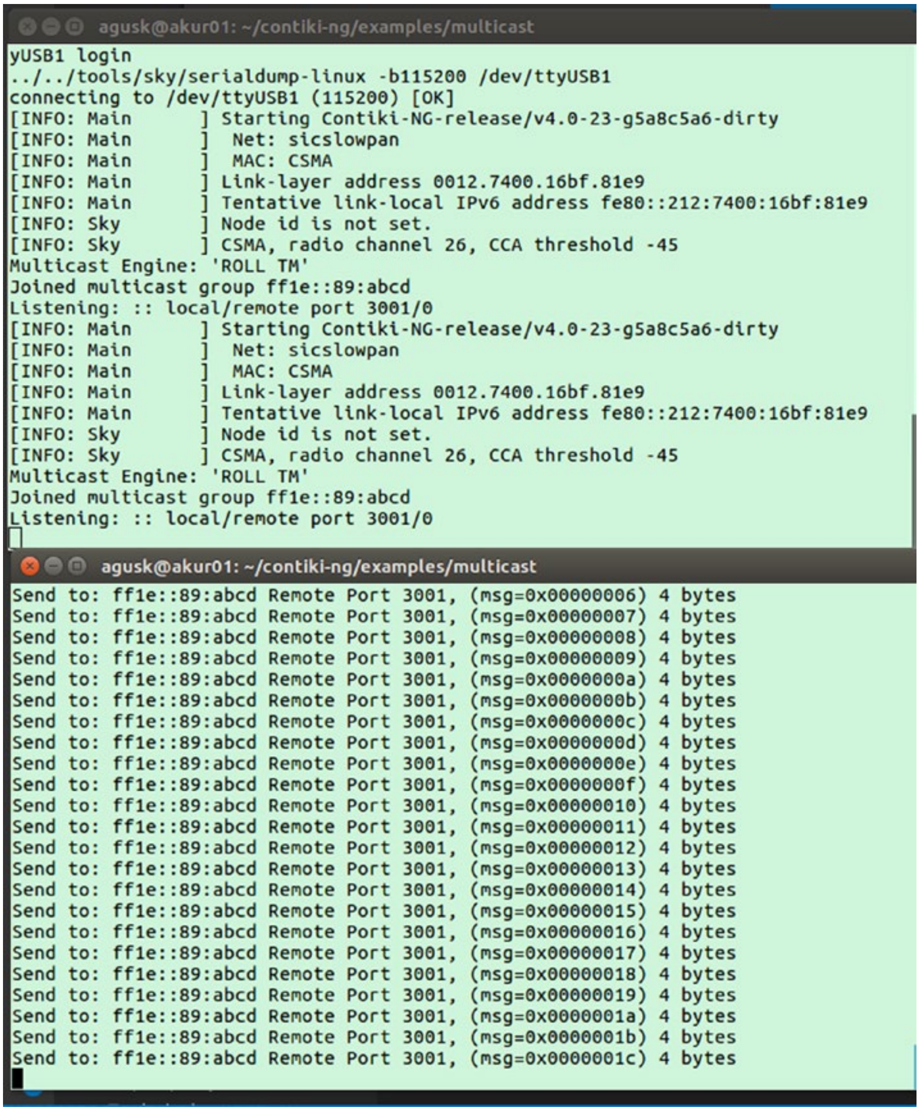
For testing, we can use a program sample from Contiki-NG. We can use the multicast project from the <contiki-ng>/examples/multicast/ folder. For this demo, we need at least three motes. One mote is deployed for sink.c and another mote is deployed for root.c. The rest should be flashed for intermediate.c.

After deploying all programs to the motes, you can try to remote in to each mote. In general, the sink.c program will listen for incoming messages from root.c. Before listening for the message, the sink.c program should join the existing multicast group by calling the join_mcast_group() function. This program listens on port 3001:

```
if(join_mcast_group() == NULL) {
    PRINTF("Failed to join multicast group\n");
    PROCESS_EXIT();
}
```

The root.c program will send a UDP message every second. This is done by calling the uip_udp_packet_send() function. The intermediate.c program does not join the existing multicast group. Since the intermediate.c program has been activated for RPL classic routing, this program can forward any multicast message.

The demo of the multicast project can be seen in Figure 6-28. You can see the program output from the sink.c and root.c programs.

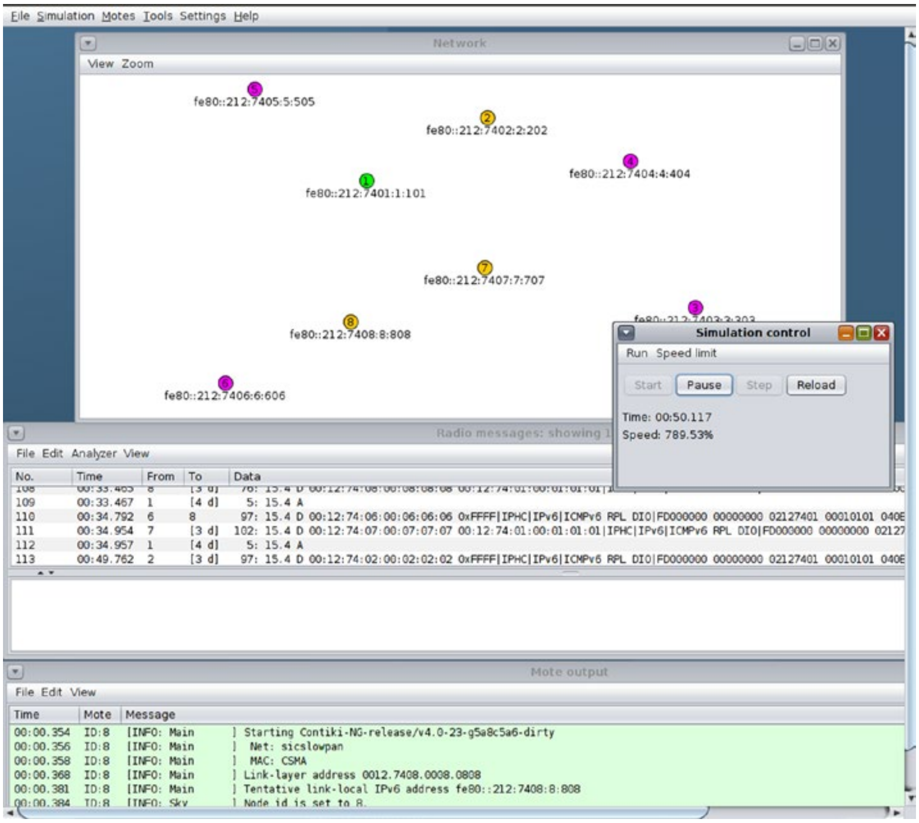


```
yUSB1 login
../../tools/sky/serialdump-linux -b115200 /dev/ttyUSB1
connecting to /dev/ttyUSB1 (115200) [OK]
[INFO: Main      ] Starting Contiki-NG-release/v4.0-23-g5a8c5a6-dirty
[INFO: Main      ]  Net: sicslowpan
[INFO: Main      ]  MAC: CSMA
[INFO: Main      ] Link-layer address 0012.7400.16bf.81e9
[INFO: Main      ] Tentative link-local IPv6 address fe80::212:7400:16bf:81e9
[INFO: Sky       ] Node id is not set.
[INFO: Sky       ] CSMA, radio channel 26, CCA threshold -45
Multicast Engine: 'ROLL TM'
Joined multicast group ff1e::89:abcd
Listening: :: local/remote port 3001/0
[INFO: Main      ] Starting Contiki-NG-release/v4.0-23-g5a8c5a6-dirty
[INFO: Main      ]  Net: sicslowpan
[INFO: Main      ]  MAC: CSMA
[INFO: Main      ] Link-layer address 0012.7400.16bf.81e9
[INFO: Main      ] Tentative link-local IPv6 address fe80::212:7400:16bf:81e9
[INFO: Sky       ] Node id is not set.
[INFO: Sky       ] CSMA, radio channel 26, CCA threshold -45
Multicast Engine: 'ROLL TM'
Joined multicast group ff1e::89:abcd
Listening: :: local/remote port 3001/0
```

```
Send to: ff1e::89:abcd Remote Port 3001, (msg=0x00000006) 4 bytes
Send to: ff1e::89:abcd Remote Port 3001, (msg=0x00000007) 4 bytes
Send to: ff1e::89:abcd Remote Port 3001, (msg=0x00000008) 4 bytes
Send to: ff1e::89:abcd Remote Port 3001, (msg=0x00000009) 4 bytes
Send to: ff1e::89:abcd Remote Port 3001, (msg=0x0000000a) 4 bytes
Send to: ff1e::89:abcd Remote Port 3001, (msg=0x0000000b) 4 bytes
Send to: ff1e::89:abcd Remote Port 3001, (msg=0x0000000c) 4 bytes
Send to: ff1e::89:abcd Remote Port 3001, (msg=0x0000000d) 4 bytes
Send to: ff1e::89:abcd Remote Port 3001, (msg=0x0000000e) 4 bytes
Send to: ff1e::89:abcd Remote Port 3001, (msg=0x0000000f) 4 bytes
Send to: ff1e::89:abcd Remote Port 3001, (msg=0x00000010) 4 bytes
Send to: ff1e::89:abcd Remote Port 3001, (msg=0x00000011) 4 bytes
Send to: ff1e::89:abcd Remote Port 3001, (msg=0x00000012) 4 bytes
Send to: ff1e::89:abcd Remote Port 3001, (msg=0x00000013) 4 bytes
Send to: ff1e::89:abcd Remote Port 3001, (msg=0x00000014) 4 bytes
Send to: ff1e::89:abcd Remote Port 3001, (msg=0x00000015) 4 bytes
Send to: ff1e::89:abcd Remote Port 3001, (msg=0x00000016) 4 bytes
Send to: ff1e::89:abcd Remote Port 3001, (msg=0x00000017) 4 bytes
Send to: ff1e::89:abcd Remote Port 3001, (msg=0x00000018) 4 bytes
Send to: ff1e::89:abcd Remote Port 3001, (msg=0x00000019) 4 bytes
Send to: ff1e::89:abcd Remote Port 3001, (msg=0x0000001a) 4 bytes
Send to: ff1e::89:abcd Remote Port 3001, (msg=0x0000001b) 4 bytes
Send to: ff1e::89:abcd Remote Port 3001, (msg=0x0000001c) 4 bytes
```

Figure 6-28. *Multicast demo on Sky mote*

If you don't have three motes or more, you still can simulate this project using COOJA. You can open the `<contiki-ng>/examples/multicast/multicast.csc` file in the COOJA application. There are eight motes in this simulation. After loading the project into COOJA, you can run the multicast simulation. You can see the simulation output in Figure 6-29. You can see all messages from the motes in the Radio Messages window.



```
Time: 00:50.117
Speed: 789.53%
```

```
No.   Time       From  To     Data
109   00:33.467  1     [4 d]    5: 15.4 A
110   00:34.792  6     8       97: 15.4 D 00:12:74:06:00:06:06:06 0xFFFF|IPHC|IPv6|ICMPv6 RPL DIO|FD000000 00000000 02127401 00010101 040E
111   00:34.954  7     [3 d]  102: 15.4 D 00:12:74:07:00:07:07:07 00:12:74:01:00:01:01:01|IPHC|IPv6|ICMPv6 RPL DIO|FD000000 00000000 02127
112   00:34.957  1     [4 d]    5: 15.4 A
113   00:49.762  2     [3 d]   97: 15.4 D 00:12:74:02:00:02:02:02 0xFFFF|IPHC|IPv6|ICMPv6 RPL DIO|FD000000 00000000 02127401 00010101 040E
```

```
Time       Mote  Message
00:00.354  ID:8  [INFO: Main      ] Starting Contiki-NG-release/v4.0-23-g5a8c5a6-dirty
00:00.356  ID:8  [INFO: Main      ]  Net: sicslowpan
00:00.358  ID:8  [INFO: Main      ]  MAC: CSMA
00:00.368  ID:8  [INFO: Main      ] Link-layer address 0012.7408.0008.0808
00:00.381  ID:8  [INFO: Main      ] Tentative link-local IPv6 address fe80::212:7408:8:808
00:00.384  ID:8  [INFO: Sky       ] Node id is set to 8.
```

Figure 6-29. *Multicast demo on COOJA tool*

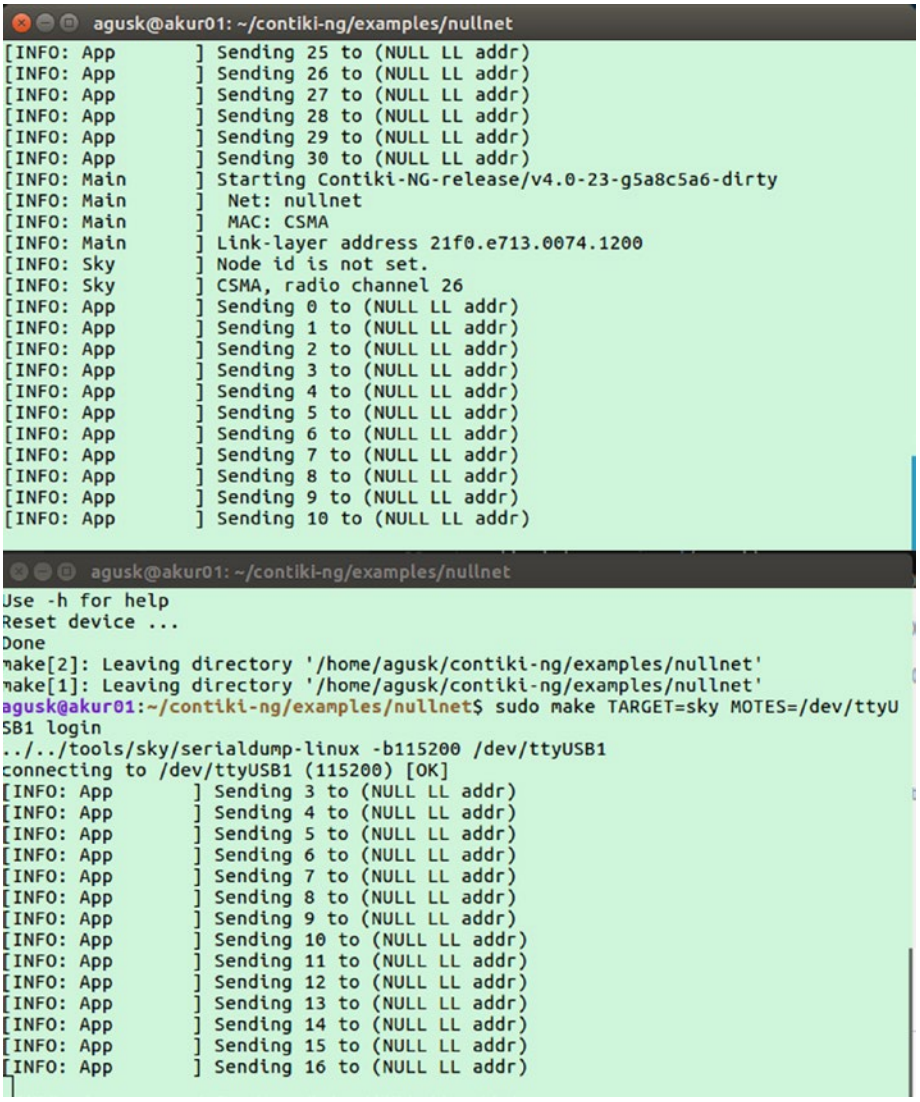
Contiki-NG NullNet

If you want to investigate a packet among Contiki-NG network stack layers, you can use NullNet. To work with NullNet, add this script to the `Makefile` file:

```
MAKE_NET = MAKE_NET_NULLNET
```

If you want to send data, you should the data and its size in the `nullnet_buf` and `nullnet_len` variables, which are pre-defined from `net/nullnet/nullnet.h`. Then, send the data by calling `NETSTACK_NETWORK.output(NULL)`. To receive packets from NullNet, you call the `nullnet_set_input_callback(callback_func)` function with the passing callback function.

For this demo, you can run program samples from the `<contiki-ng>/examples/nullnet` folder. There are two demos: broadcast and unicast. You can run these programs on motes directly or in the COOJA application. You can see my program output in Figure 6-30 on a mote from the demo samples on Contiki-NG motes.



```
agusk@akur01: ~/contiki-ng/examples/nullnet
[INFO: App       ] Sending 25 to (NULL LL addr)
[INFO: App       ] Sending 26 to (NULL LL addr)
[INFO: App       ] Sending 27 to (NULL LL addr)
[INFO: App       ] Sending 28 to (NULL LL addr)
[INFO: App       ] Sending 29 to (NULL LL addr)
[INFO: App       ] Sending 30 to (NULL LL addr)
[INFO: Main      ] Starting Contiki-NG-release/v4.0-23-g5a8c5a6-dirty
[INFO: Main      ]  Net: nullnet
[INFO: Main      ]  MAC: CSMA
[INFO: Main      ] Link-layer address 21f0.e713.0074.1200
[INFO: Sky       ] Node id is not set.
[INFO: Sky       ] CSMA, radio channel 26
[INFO: App       ] Sending 0 to (NULL LL addr)
[INFO: App       ] Sending 1 to (NULL LL addr)
[INFO: App       ] Sending 2 to (NULL LL addr)
[INFO: App       ] Sending 3 to (NULL LL addr)
[INFO: App       ] Sending 4 to (NULL LL addr)
[INFO: App       ] Sending 5 to (NULL LL addr)
[INFO: App       ] Sending 6 to (NULL LL addr)
[INFO: App       ] Sending 7 to (NULL LL addr)
[INFO: App       ] Sending 8 to (NULL LL addr)
[INFO: App       ] Sending 9 to (NULL LL addr)
[INFO: App       ] Sending 10 to (NULL LL addr)
```

```
agusk@akur01: ~/contiki-ng/examples/nullnet
Use -h for help
Reset device ...
Done
make[2]: Leaving directory '/home/agusk/contiki-ng/examples/nullnet'
make[1]: Leaving directory '/home/agusk/contiki-ng/examples/nullnet'
agusk@akur01:~/contiki-ng/examples/nullnet$ sudo make TARGET=sky MOTES=/dev/ttyU
SB1 login
../../tools/sky/serialdump-linux -b115200 /dev/ttyUSB1
connecting to /dev/ttyUSB1 (115200) [OK]
[INFO: App       ] Sending 3 to (NULL LL addr)
[INFO: App       ] Sending 4 to (NULL LL addr)
[INFO: App       ] Sending 5 to (NULL LL addr)
[INFO: App       ] Sending 6 to (NULL LL addr)
[INFO: App       ] Sending 7 to (NULL LL addr)
[INFO: App       ] Sending 8 to (NULL LL addr)
[INFO: App       ] Sending 9 to (NULL LL addr)
[INFO: App       ] Sending 10 to (NULL LL addr)
[INFO: App       ] Sending 11 to (NULL LL addr)
[INFO: App       ] Sending 12 to (NULL LL addr)
[INFO: App       ] Sending 13 to (NULL LL addr)
[INFO: App       ] Sending 14 to (NULL LL addr)
[INFO: App       ] Sending 15 to (NULL LL addr)
[INFO: App       ] Sending 16 to (NULL LL addr)
```

Figure 6-30. *NullNet demo on Sky mote*

You can also test this program demo using COOJA. Just select the `nullnet-broadcast.csc` and `nullnet-unicast.csc` files from the COOJA application. After they are loaded, you can run these demos and see radio messages from COOJA application and review pack flow.

6LoWPAN Network

6LoWPAN is an acronym for IPv6 over Low-Power Wireless Personal Area Networks. 6LoWPAN is an open standard defined in RFC 6282. This standard enables WSN motes to communicate with other systems via an Internet network.

In this section, we will learn the basics of 6LoWPAN and how to implement it on the Contiki-NG platform.

A Brief Introduction

6LoWPAN is a network standard used to enable WSN motes to communicate with external networks, such as Internet networks. 6LoWPAN uses IPv6 as the identity for all motes. A 6LoWPAN network is shown in Figure 6-31.

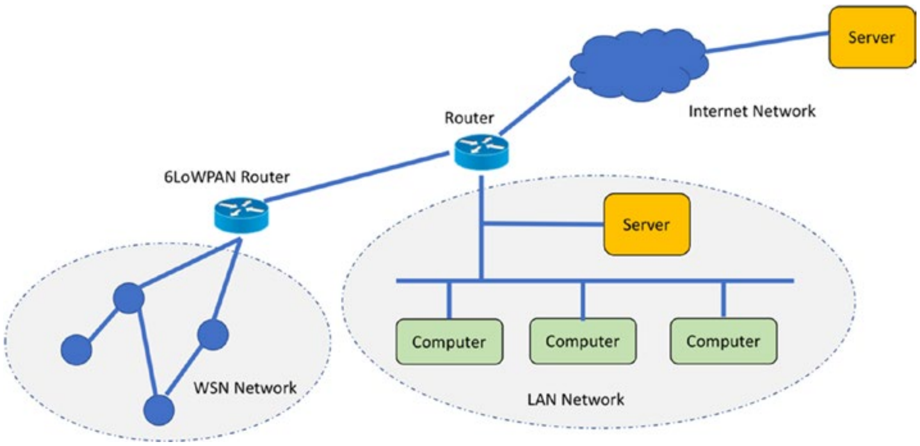


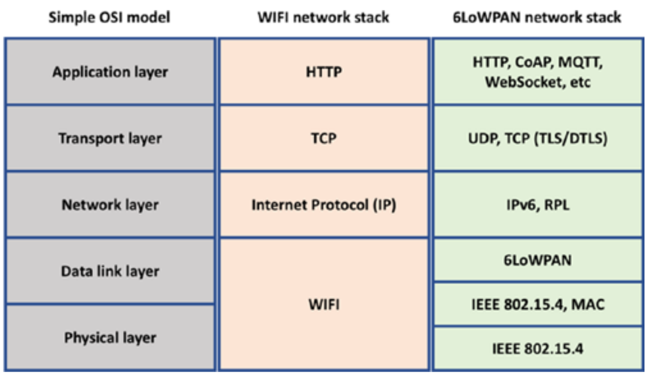
Figure 6-31. *6LoWPAN network*

WSN networks apply IPv6 for all communication. Each mote can communicate with the other motes. If one mote wants to communicate with an external system, such as a server, computer, or any legacy application in a different network, the mote just sends a message as usual. The 6LoWPAN router will take responsibility for communication between internal and external networks.

A 6LoWPAN router will record all addresses from motes and other network devices that are connected to the 6LoWPAN router. If an external system such as a server sends a message to one of the WSN motes in the WSN network, the 6LoWPAN router will forward the message to the mote. Otherwise, 6LoWPAN will inform the requester of failure.

In a network-stack view, we can compare a 6LoWPAN network to a WiFi network from the OSI layer side. You can see this comparison in Figure 6-32.

As you can see in Figure 6-32, 6LoWPAN works on the data-link layer in the OSI model. This standard uses IEEE 802.15.4 for physical layer implementation. In the upper layer of the 6LoWPAN, this standard applies IPv6 on RPL.



Simple OSI model	WIFI network stack	6LoWPAN network stack
Application layer	HTTP	HTTP, CoAP, MQTT, WebSocket, etc
Transport layer	TCP	UDP, TCP (TLS/DTLS)
Network layer	Internet Protocol (IP)	IPv6, RPL
Data link layer	WIFI	6LoWPAN
		IEEE 802.15.4, MAC
Physical layer		IEEE 802.15.4

Figure 6-32. *Comparing WiFi and 6LoWPAN to OSI model*

In the next section, we will try to implement 6LoWPAN on Contiki-NG.

Implementing a 6LoWPAN Network on Contiki-NG

Contiki-NG implements the 6LoWPAN network stack via an RPL border router that acts as a 6LoWPAN router. You can see a network diagram in Figure 6-33 for implementing 6LoWPAN on the Contiki-NG platform. You can put the RPL border router on a computer or a Raspberry Pi or any network device.

How do you implement an RPL border router in Contiki-NG?

Basically, you need a Contiki-NG mote as the RPL border router mote. This mote will work as a bridge to serve all requests from motes in the WSN network or network devices from an external network. To create an RPL border router mote, you should add the `rpl-border-router` library into your project. You can add this script to your `Makefile` file:

```
MODULES += os/services/rpl-border-router
```

Then, run a program, called tunslip6, from Contiki-NG. You can find it in the `<contiki-ng>/tools/` folder. This tool will communicate with a mote that has already been deployed as an RPL border router via serial port. You can type this command:

```
$ sudo ./tunslip6 <prefic> -s <serial_port>
```

`<prefic>` is a prefix from the IPv6 address that will assign to all motes on the RPL border router application. `<serial_port>` is a serial port from the mote running the RPL border router program.

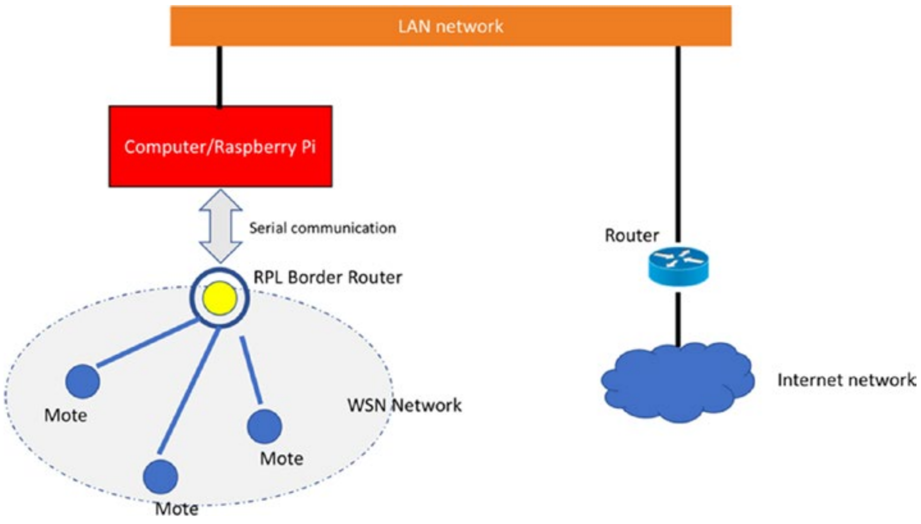


Figure 6-33. *Implementing 6LoWPAN network on Contiki-NG*

For this demo, we can run a program sample from the `<contiki-ng>/examples/rpl-border-router/` folder. This project includes an RPL border router and web server modules. We need at least two motes to simulate the 6LoWPAN router and its communication.

Compile this project and flash it to one of the Contiki-NG motes. After it has been deployed to the mote, you can work remotely on the non–border router mote to see the assigned IPv6 address.

Last, you should run the tunslip6 program on the computer/Raspberry Pi to which the RPL border router mote was attached. You can run this command on the rpl-border-router project:

```
$ make TARGET=srf06-cc26xx BOARD=launchpad/cc2650 connect-
router
```

After being executed, that command will run tunslip6 with a default port. You should probably change the values for the target mote platform and its serial port.

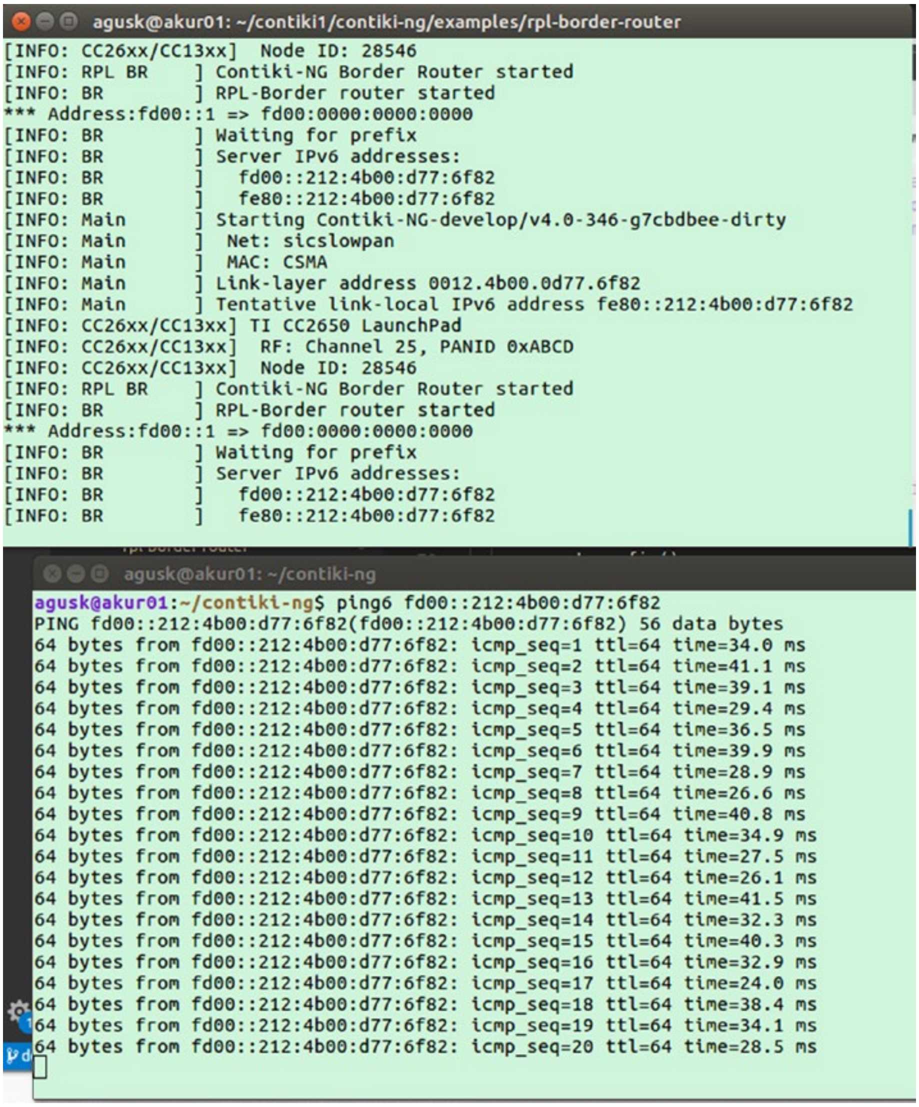
By default, the RPL border router has an IPv6 address of `fd00::1/64`. You can change it in your `Makefile`. For instance, if you define the prefix of your IPv6 address as `fd00::1/64`, all motes within the WSN network will be assigned as `fd00::xxxx`. In this demo, my mote is assigned as `fd00::212::4b00::d77::6fd2`.

Now you can ping the mote using the assigned IPv6 address from your computer. For instance, type this command:

```
$ ping6 fd00::212:4b00:d77:6fd2
```

This program will get a response from the target mote because this mote can communicate with the computer through the RPL border router. You can see the program output in Figure 6-34. I ping my mote from Linux Ubuntu. It shows my computer can contact the Contiki-NG mote.

If you do not see a list of IPv6 addresses from your motes, you can restart your RPL border router application, tunslip6. Then, see the list of IPv6 addresses from the motes.



agusk@akur01: ~/contiki1/contiki-ng/examples/rpl-border-router

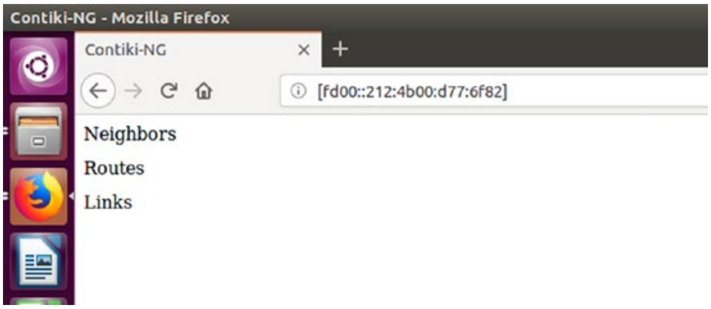
```
[INFO: CC26xx/CC13xx]  Node ID: 28546
[INFO: RPL BR      ] Contiki-NG Border Router started
[INFO: BR          ] RPL-Border router started
*** Address:fd00::1 => fd00:0000:0000:0000
[INFO: BR          ] Waiting for prefix
[INFO: BR          ] Server IPv6 addresses:
[INFO: BR          ]   fd00::212:4b00:d77:6f82
[INFO: BR          ]   fe80::212:4b00:d77:6f82
[INFO: Main        ] Starting Contiki-NG-develop/v4.0-346-g7cbdbee-dirty
[INFO: Main        ]  Net: sicslowpan
[INFO: Main        ]  MAC: CSMA
[INFO: Main        ] Link-layer address 0012.4b00.0d77.6f82
[INFO: Main        ] Tentative link-local IPv6 address fe80::212:4b00:d77:6f82
[INFO: CC26xx/CC13xx] TI CC2650 LaunchPad
[INFO: CC26xx/CC13xx]  RF: Channel 25, PANID 0xABCD
[INFO: CC26xx/CC13xx]  Node ID: 28546
[INFO: RPL BR      ] Contiki-NG Border Router started
[INFO: BR          ] RPL-Border router started
*** Address:fd00::1 => fd00:0000:0000:0000
[INFO: BR          ] Waiting for prefix
[INFO: BR          ] Server IPv6 addresses:
[INFO: BR          ]   fd00::212:4b00:d77:6f82
[INFO: BR          ]   fe80::212:4b00:d77:6f82
```

agusk@akur01: ~/contiki-ng

```
agusk@akur01:~/contiki-ng$ ping6 fd00::212:4b00:d77:6f82
PING fd00::212:4b00:d77:6f82(fd00::212:4b00:d77:6f82) 56 data bytes
64 bytes from fd00::212:4b00:d77:6f82: icmp_seq=1 ttl=64 time=34.0 ms
64 bytes from fd00::212:4b00:d77:6f82: icmp_seq=2 ttl=64 time=41.1 ms
64 bytes from fd00::212:4b00:d77:6f82: icmp_seq=3 ttl=64 time=39.1 ms
64 bytes from fd00::212:4b00:d77:6f82: icmp_seq=4 ttl=64 time=29.4 ms
64 bytes from fd00::212:4b00:d77:6f82: icmp_seq=5 ttl=64 time=36.5 ms
64 bytes from fd00::212:4b00:d77:6f82: icmp_seq=6 ttl=64 time=39.9 ms
64 bytes from fd00::212:4b00:d77:6f82: icmp_seq=7 ttl=64 time=28.9 ms
64 bytes from fd00::212:4b00:d77:6f82: icmp_seq=8 ttl=64 time=26.6 ms
64 bytes from fd00::212:4b00:d77:6f82: icmp_seq=9 ttl=64 time=40.8 ms
64 bytes from fd00::212:4b00:d77:6f82: icmp_seq=10 ttl=64 time=34.9 ms
64 bytes from fd00::212:4b00:d77:6f82: icmp_seq=11 ttl=64 time=27.5 ms
64 bytes from fd00::212:4b00:d77:6f82: icmp_seq=12 ttl=64 time=26.1 ms
64 bytes from fd00::212:4b00:d77:6f82: icmp_seq=13 ttl=64 time=41.5 ms
64 bytes from fd00::212:4b00:d77:6f82: icmp_seq=14 ttl=64 time=32.3 ms
64 bytes from fd00::212:4b00:d77:6f82: icmp_seq=15 ttl=64 time=40.3 ms
64 bytes from fd00::212:4b00:d77:6f82: icmp_seq=16 ttl=64 time=32.9 ms
64 bytes from fd00::212:4b00:d77:6f82: icmp_seq=17 ttl=64 time=24.0 ms
64 bytes from fd00::212:4b00:d77:6f82: icmp_seq=18 ttl=64 time=38.4 ms
64 bytes from fd00::212:4b00:d77:6f82: icmp_seq=19 ttl=64 time=34.1 ms
64 bytes from fd00::212:4b00:d77:6f82: icmp_seq=20 ttl=64 time=28.5 ms
```

Figure 6-34. *Performing ping on one of the Contiki-NG motes from a computer*

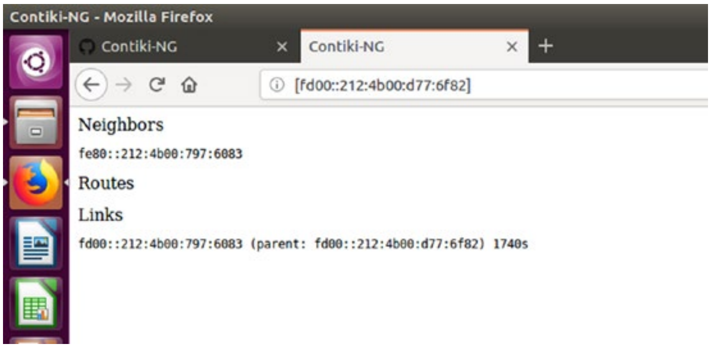
If you use a program sample from `<contiki-ng>/examples/rpl-border-router/`, you should get the web server within the program. You can test by opening a browser and navigating to `http://[ip6_address_from_mote]`. You can see my browser output in Figure 6-35.



Neighbors
Routes
Links

Figure 6-35. *Accessing web server on Contiki-NG mote from computer browser*

If you have another mote, you can upload the Contiki-NG firmware to that mote. Then, the RPL border router will detect it. If you open a browser and navigate to the IPv6 address from the RPL border router mote, you should show its neighbor. You should see the IPv6 address from that mote. For instance, you can see it in Figure 6-36.



Neighbors
```
fe80::212:4b00:797:6083
```
Routes
Links
```
fd00::212:4b00:797:6083 (parent: fd00::212:4b00:d77:6f82) 1740s
```

Figure 6-36. *Displaying mote neighbor on RPL border router*

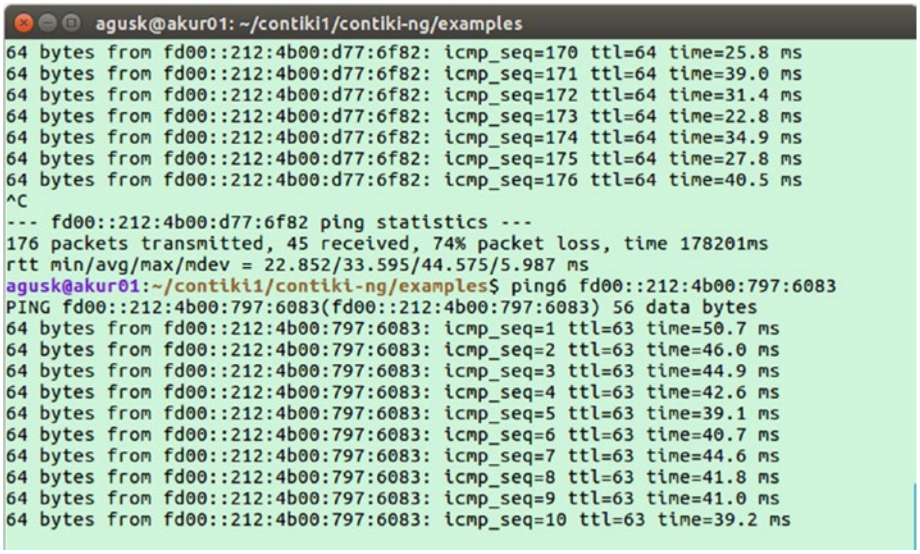
You can also test it by performing a ping. For instance, the target mote is `fd00::212:4b00:6083`. We can perform a ping as follows:

```
$ ping6 fd00::212:4b00:6083
```

You should get a response from that mote. You can see it in Figure 6-37.

Sometimes you don't see the IPv6 address from a new mote in your browser (Figure 6-36), but you know the local IPv6 address of the new mote. You can verify it by remoting into the mote with the local IPv6 address. For instance, the IPv6 address is `fe80::212:4b00:6083`. Now, change the prefix to `fd00::xxx`. The new IPv6 address shows `fd00::212:4b00:6083`. Try to ping it.

If you still have problems in which motes are not detected by the RPL border router, you probably need to restart the RPL border router mote.



```
64 bytes from fd00::212:4b00:d77:6f82: icmp_seq=170 ttl=64 time=25.8 ms
64 bytes from fd00::212:4b00:d77:6f82: icmp_seq=171 ttl=64 time=39.0 ms
64 bytes from fd00::212:4b00:d77:6f82: icmp_seq=172 ttl=64 time=31.4 ms
64 bytes from fd00::212:4b00:d77:6f82: icmp_seq=173 ttl=64 time=22.8 ms
64 bytes from fd00::212:4b00:d77:6f82: icmp_seq=174 ttl=64 time=34.9 ms
64 bytes from fd00::212:4b00:d77:6f82: icmp_seq=175 ttl=64 time=27.8 ms
64 bytes from fd00::212:4b00:d77:6f82: icmp_seq=176 ttl=64 time=40.5 ms
^C
--- fd00::212:4b00:d77:6f82 ping statistics ---
176 packets transmitted, 45 received, 74% packet loss, time 178201ms
rtt min/avg/max/mdev = 22.852/33.595/44.575/5.987 ms
agusk@akur01:~/contiki1/contiki-ng/examples$ ping6 fd00::212:4b00:797:6083
PING fd00::212:4b00:797:6083(fd00::212:4b00:797:6083) 56 data bytes
64 bytes from fd00::212:4b00:797:6083: icmp_seq=1 ttl=63 time=50.7 ms
64 bytes from fd00::212:4b00:797:6083: icmp_seq=2 ttl=63 time=46.0 ms
64 bytes from fd00::212:4b00:797:6083: icmp_seq=3 ttl=63 time=44.9 ms
64 bytes from fd00::212:4b00:797:6083: icmp_seq=4 ttl=63 time=42.6 ms
64 bytes from fd00::212:4b00:797:6083: icmp_seq=5 ttl=63 time=39.1 ms
64 bytes from fd00::212:4b00:797:6083: icmp_seq=6 ttl=63 time=40.7 ms
64 bytes from fd00::212:4b00:797:6083: icmp_seq=7 ttl=63 time=44.6 ms
64 bytes from fd00::212:4b00:797:6083: icmp_seq=8 ttl=63 time=41.8 ms
64 bytes from fd00::212:4b00:797:6083: icmp_seq=9 ttl=63 time=41.0 ms
64 bytes from fd00::212:4b00:797:6083: icmp_seq=10 ttl=63 time=39.2 ms
```

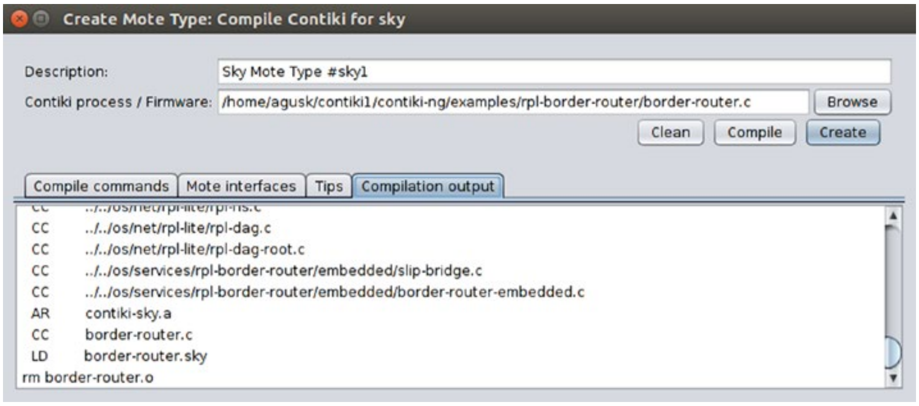
Figure 6-37. *Performing ping on other mote in WSN network from computer*

6LoWPAN Implementation using COOJA

In the previous section, we learned how to implement 6LoWPAN on a physical device from a Contiki-NG mote. In this section, we want to implement 6LoWPAN on a simulation platform through the COOJA tool.

For this demo, we will use the program sample from the `<contiki-ng>/examples/rpl-border-router/` folder. First, you can run the COOJA application. Create a new simulation project.

Next, you should add a new mote with the Sky platform. You can set `<contiki-ng>/examples/rpl-border-router/border-router.c` for the Contiki firmware, shown in Figure 6-38.


Create Mote Type: Compile Contiki for sky
Description:
Sky Mote Type #sky1
Contiki process / Firmware:
/home/agusk/contiki1/contiki-ng/examples/rpl-border-router/border-router.c
Browse
Clean
Compile
Create
Compile commands
Mote interfaces
Tips
Compilation output

```
CC      ../../os/net/rpl-lite/rpl-ns.c
CC      ../../os/net/rpl-lite/rpl-dag.c
CC      ../../os/net/rpl-lite/rpl-dag-root.c
CC      ../../os/services/rpl-border-router/embedded/slip-bridge.c
CC      ../../os/services/rpl-border-router/embedded/border-router-embedded.c
AR      contiki-sky.a
CC      border-router.c
LD      border-router.sky
rm border-router.o
```

Figure 6-38. *Add RPL border router into COOJA*

You can compile this Contiki firmware. If there is no error, you can click the Create button. In this demo, you will create one mote.

The next step is to add the serial socket tool to the mote. You can do this by right-clicking on the mote. Then, you will see the context menu shown in Figure 6-39. Select Mote tools for Sky 1 ➤ Serial Socket (SERVER).

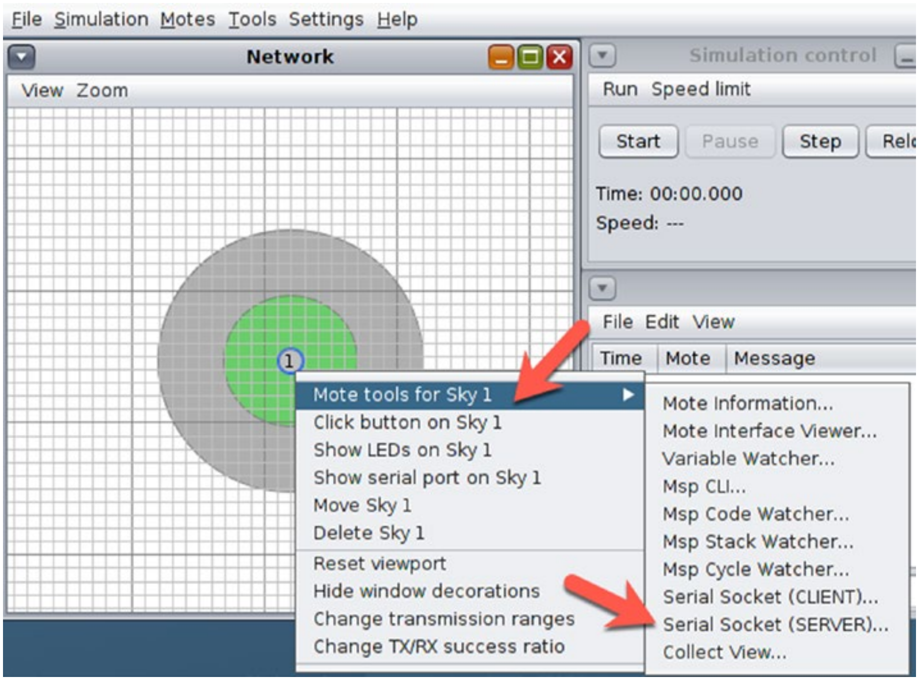
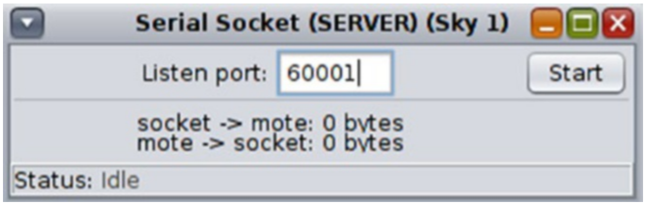


Figure 6-39. *Add serial socket tool on RPL border router mote*

You should now see the dialog shown in Figure 6-40. You can run it by clicking the Start button. We use the default listen port, 60001.



60001

socket -> mote: 0 bytes
mote -> socket: 0 bytes

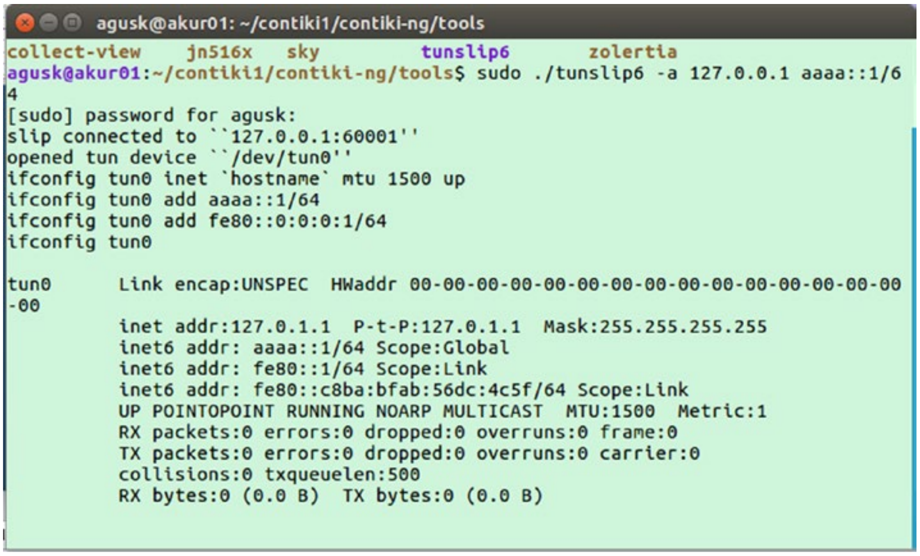
Status: Idle

Figure 6-40. *A serial socket dialog to set a listen port*

Next, you should run tunslip6 from the `<contiki-ng>/tools/` folder. You can open Terminal and navigate to `<contiki-ng>/tools/`. Then, you can run this command:

```
$ sudo ./tunslip6 -a 127.0.0.1 aaaa::1/64
```

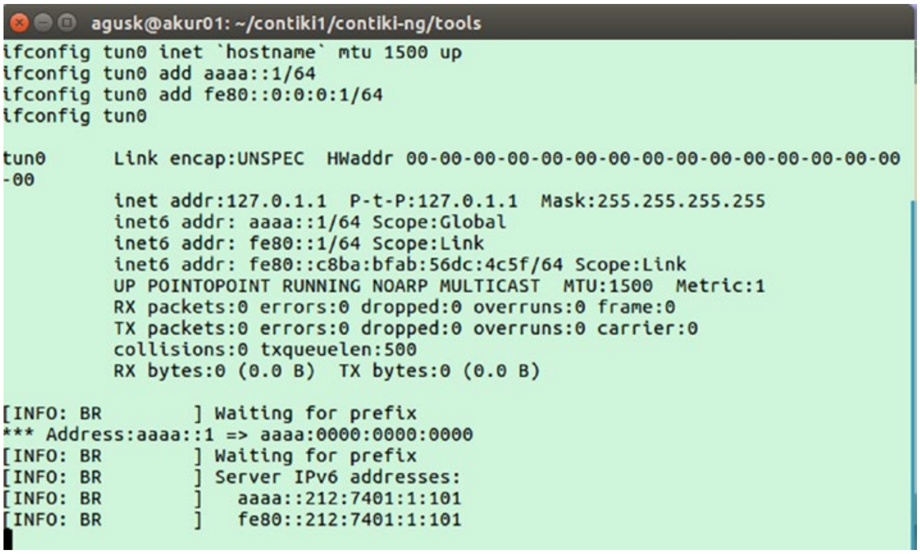
Tunslip6 will run and connect to the RPL border router from a mote within the COOJA application. You can see the program output from tunslip6 in Figure 6-41.



```
agusk@akur01: ~/contiki1/contiki-ng/tools
collect-view    jn516x   sky          tunslip6       zolertia
agusk@akur01:~/contiki1/contiki-ng/tools$ sudo ./tunslip6 -a 127.0.0.1 aaaa::1/6
4
[sudo] password for agusk:
slip connected to ``127.0.0.1:60001''
opened tun device ``/dev/tun0''
ifconfig tun0 inet `hostname` mtu 1500 up
ifconfig tun0 add aaaa::1/64
ifconfig tun0 add fe80::0:0:0:1/64
ifconfig tun0

tun0      Link encap:UNSPEC  HWaddr 00-00-00-00-00-00-00-00-00-00-00-00-00-00-00
-00
          inet addr:127.0.1.1  P-t-P:127.0.1.1  Mask:255.255.255.255
          inet6 addr: aaaa::1/64 Scope:Global
          inet6 addr: fe80::1/64 Scope:Link
          inet6 addr: fe80::c8ba:bfab:56dc:4c5f/64 Scope:Link
          UP POINTOPOINT RUNNING NOARP MULTICAST  MTU:1500  Metric:1
          RX packets:0 errors:0 dropped:0 overruns:0 frame:0
          TX packets:0 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:500
          RX bytes:0 (0.0 B)  TX bytes:0 (0.0 B)
```

Figure 6-41. *Running tunslip6 program on local computer*

Once tunslip6 is running, you can run the simulation on COOJA. This makes the mote run. You can see the IPv6 translator of the mote from tunslip6 in Figure 6-42.



```
agusk@akur01: ~/contiki1/contiki-ng/tools
ifconfig tun0 inet `hostname` mtu 1500 up
ifconfig tun0 add aaaa::1/64
ifconfig tun0 add fe80::0:0:0:1/64
ifconfig tun0

tun0      Link encap:UNSPEC  HWaddr 00-00-00-00-00-00-00-00-00-00-00-00-00-00-00
-00
          inet addr:127.0.1.1  P-t-P:127.0.1.1  Mask:255.255.255.255
          inet6 addr: aaaa::1/64 Scope:Global
          inet6 addr: fe80::1/64 Scope:Link
          inet6 addr: fe80::c8ba:bfab:56dc:4c5f/64 Scope:Link
          UP POINTOPOINT RUNNING NOARP MULTICAST  MTU:1500  Metric:1
          RX packets:0 errors:0 dropped:0 overruns:0 frame:0
          TX packets:0 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:500
          RX bytes:0 (0.0 B)  TX bytes:0 (0.0 B)

[INFO: BR        ] Waiting for prefix
*** Address:aaaa::1 => aaaa:0000:0000:0000
[INFO: BR        ] Waiting for prefix
[INFO: BR        ] Server IPv6 addresses:
[INFO: BR        ]   aaaa::212:7401:1:101
[INFO: BR        ]   fe80::212:7401:1:101
```

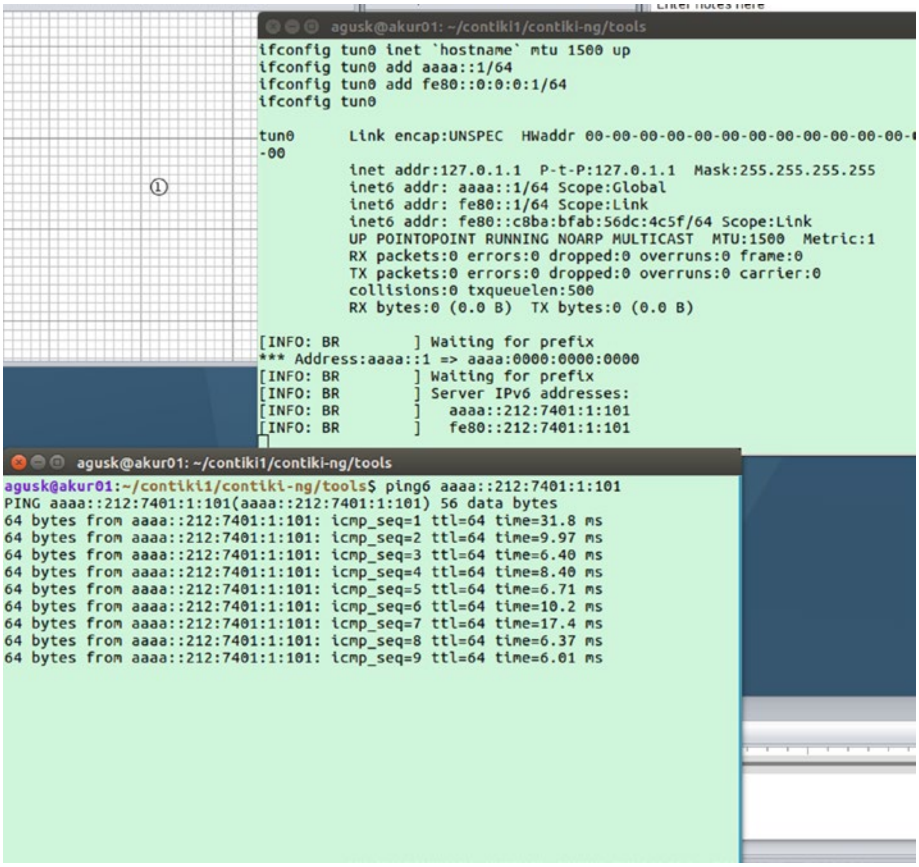
Figure 6-42. *Detecting IPv6 address on tunslip6 tool*

You should see the IPv6 address of the COOJA mote in Terminal. For instance, my mote IPv6 address is `aaaa::212:7401:1:101`. Now, you can open a new Terminal. Then, try to perform `ping6`.

You can type this command:

```
$ ping6 aaaa::212:7401:1:101
```

You should get responses from your COOJA mote. You can see my `ping6` response in Figure 6-43.



```
agusk@akur01: ~/contiki1/contiki-ng/tools
ifconfig tun0 inet `hostname` mtu 1500 up
ifconfig tun0 add aaaa::1/64
ifconfig tun0 add fe80::0:0:0:1/64
ifconfig tun0

tun0      Link encap:UNSPEC  HWaddr 00-00-00-00-00-00-00-00-00-00-00-00-0
-00
          inet addr:127.0.1.1  P-t-P:127.0.1.1  Mask:255.255.255.255
          inet6 addr: aaaa::1/64 Scope:Global
          inet6 addr: fe80::1/64 Scope:Link
          inet6 addr: fe80::c8ba:bfab:56dc:4c5f/64 Scope:Link
          UP POINTOPOINT RUNNING NOARP MULTICAST  MTU:1500  Metric:1
          RX packets:0 errors:0 dropped:0 overruns:0 frame:0
          TX packets:0 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:500
          RX bytes:0 (0.0 B)  TX bytes:0 (0.0 B)

[INFO: BR        ] Waiting for prefix
*** Address:aaaa::1 => aaaa:0000:0000:0000
[INFO: BR        ] Waiting for prefix
[INFO: BR        ] Server IPv6 addresses:
[INFO: BR        ]   aaaa::212:7401:1:101
[INFO: BR        ]   fe80::212:7401:1:101
```

```
agusk@akur01: ~/contiki1/contiki-ng/tools
agusk@akur01:~/contiki1/contiki-ng/tools$ ping6 aaaa::212:7401:1:101
PING aaaa::212:7401:1:101(aaaa::212:7401:1:101) 56 data bytes
64 bytes from aaaa::212:7401:1:101: icmp_seq=1 ttl=64 time=31.8 ms
64 bytes from aaaa::212:7401:1:101: icmp_seq=2 ttl=64 time=9.97 ms
64 bytes from aaaa::212:7401:1:101: icmp_seq=3 ttl=64 time=6.40 ms
64 bytes from aaaa::212:7401:1:101: icmp_seq=4 ttl=64 time=8.40 ms
64 bytes from aaaa::212:7401:1:101: icmp_seq=5 ttl=64 time=6.71 ms
64 bytes from aaaa::212:7401:1:101: icmp_seq=6 ttl=64 time=10.2 ms
64 bytes from aaaa::212:7401:1:101: icmp_seq=7 ttl=64 time=17.4 ms
64 bytes from aaaa::212:7401:1:101: icmp_seq=8 ttl=64 time=6.37 ms
64 bytes from aaaa::212:7401:1:101: icmp_seq=9 ttl=64 time=6.01 ms
```

Figure 6-43. *Pinging a mote from computer*

To get more practice, you can run a web server program on a new mote in COOJA. Then, you can access that web server from a browser on a local computer.

Build Your Own RESTful Server for Contiki-NG

You have learned how to build a 6LoWPAN with RPL border router. In this section, we will build a simple project based on 6LoWPAN. We will develop WebSense, which publishes sensor values to the web server. Since a Contiki-NG mote has limited resources, it cannot serve many requests. To address this issue, we can implement a middleware server—for instance, a RESTful server.

Each mote will send a result of sensing to the RESTful server. Then, the RESTful server will take over to distribute the data to all requesters. A RESTful server can run on top of a proven web server, such as Apache, nginx, and IIS.

WebSense is shown in Figure 6-44. Each mote can communicate with the RESTful server through the 6LoWPAN router. A client that wants to consume sensor data should open a connection to the RESTful server through WebSocket.

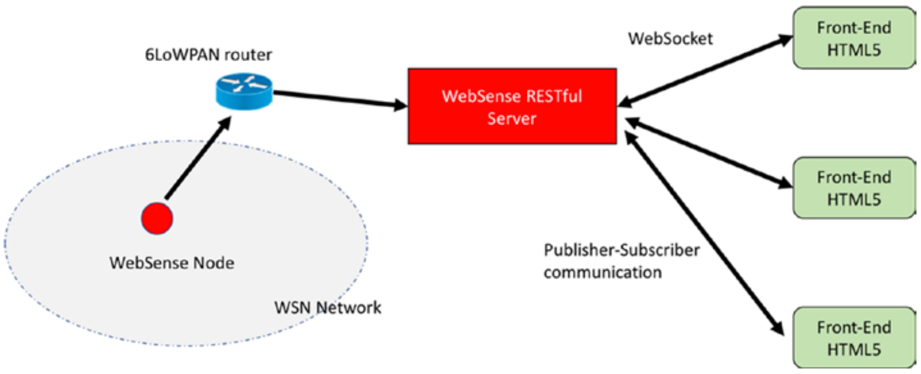


Figure 6-44. *Logic design for the WebSense project*

A client system will be implemented using HTML5 with WebSocket API. Sensor data will be visualized in the HTML5 application. Also, the WebSense RESTful server will apply Node.js.

We will implement this WebSense project in the next section.

Preparation

First, we should have two mote devices. One mote will be used for the 6LoWPAN router. The rest will be applied for WebSense node implementation.

Since our RESTful server uses Node.js, your computer should install Node.js runtime. You should install all required libraries to run Node.js. Type these commands:

```
$ sudo apt-get update
$ sudo apt-get install build-essential
```

We will use Node.js LTS version. For instance, I use Node.js LTS 6.x. You can install it by typing these commands:

```
$ curl -sL https://deb.nodesource.com/setup_6.x | sudo -E bash -
$ sudo apt-get install nodejs
```

The next step is to develop a program for the project. We will do so in the next section.

Implementing the Demo

We will implement the WebSense project as shown in Figure 6-45. It is a physical design from our demo. We deploy the RPL border router into one of the motes. This mote will be attached to a computer that will deploy Node.js too. This project will use real mote devices. You can also use COOJA for testing.

Computers and server machines should be connected to a network in order to simulate sensor data visualization.

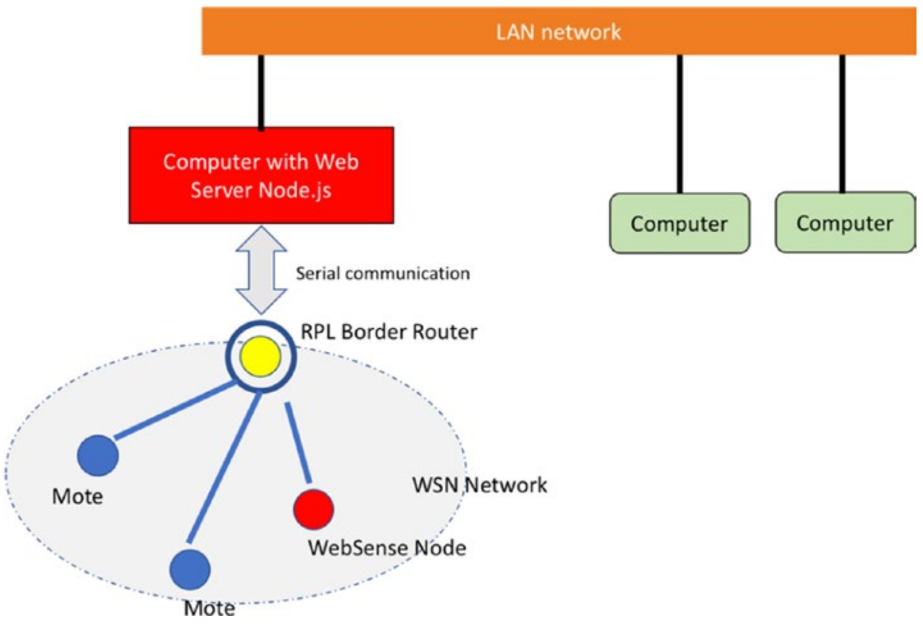


Figure 6-45. *Implementing WebSense project*

To implement this demo, we will perform the following tasks:

- Implement 6LoWPAN router.
- Develop a program for WebSense node.
- Develop a program for RESTful server.
- Test the project.

Each task will be presented in the following sections.

Implementing 6LoWPAN Router

To implement the 6LoWPAN router, we deploy the RPL border router module into the mote. In a previous section, you learned about 6LoWPAN router implementation. We will use it again in this project.

Select one of the motes to become a 6LoWPAN router. Attach it into a computer and run `connect-router` or `run tunslip6` programs manually with specific port and address settings.

Writing a Program for WebSense Node

In this section, we will develop a program for the WebSense node. The goal of this program is to serve all requests for sensor data. Technically, the program will run a mini web server and serve HTTP requests. Once the RESTful server requests sensor data, this node will send it. To simplify this demo, the program will generate a random value for sensor data.

You can see the project structure in Figure 6-46. You can create a folder, called `websense`. We put some files in it, such as `Makefile`, `project-conf.h`, and `websense.c`. For web server implementation, we use the `httpd-simple` module from Contiki-NG.

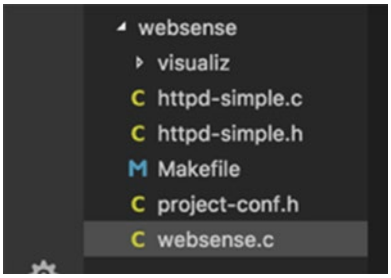

```
websense
  visualiz
  httpd-simple.c
  httpd-simple.h
  Makefile
  project-conf.h
  websense.c
```

Figure 6-46. *Project structure for WebSense node*

The application will serve requests for sensor data. This task will be handled in `websense.c` in `generate_routes()` function. You can write this code as follows:

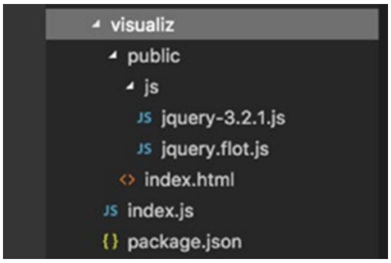
```
static
PT_THREAD(generate_routes(struct httpd_state *s))
{
  char buff[15];

  PSOCK_BEGIN(&s->sout);

  int temperature = 15 + rand() % 25;

  sprintf(buff,"{\"temp\":%u}", temperature);
  printf("send json to requester\n");

  SEND_STRING(&s->sout, buff);


  PSOCK_END(&s->sout);
}
```

We also need to modify `httpd-simple.c` in order to cover JSON requests. We declare `http_content_type_json` for JSON content. Then, we pass it into the HTTP header as follows:

```
const char http_content_type_json[] = "Content-type:
application/json\r\n\r\n";
static
PT_THREAD(send_headers(struct httpd_state *s, const char
*statushdr))
{
  /* char *ptr; */

  PSOCK_BEGIN(&s->sout);

  SEND_STRING(&s->sout, statushdr);
  SEND_STRING(&s->sout, http_content_type_json);
  PSOCK_END(&s->sout);
}
```

Writing a Program for RESTful Server

A RESTful server will run a web server on top of Node.js. We build the project structure that is shown in Figure 6-47. To visualize sensor data, we apply `jQuery` (`https://jquery.com`) and `Flot` (`http://www.flotcharts.org`) libraries for JavaScript. Download those files. Then, you can put those files into the `<project>/public/js` folder.



```
visualiz
  public
    js
      jquery-3.2.1.js
      jquery.flot.js
    index.html
  index.js
  package.json
```

Figure 6-47. *Project structure for RESTful server*

The application runs with the Node.js runtime. Make sure you have already installed it. Next, we install required the libraries for the RESTful server. We will use `Express` (`http://expressjs.com`) for the web framework and `Socket.io` (`https://socket.io`) for WebSocket implementation for Node.js.

First, create a `package.json` file inside the project folder. You can type these scripts:

```
{
  "name": "sensor",
  "version": "1.0.0",
  "description": "visualizing real-time sensor",
  "main": "index.js",
  "scripts": {
    "test": "echo \"Error: no test specified\" && exit 1"
  },
  "author": "Agus Kurniawan",
  "dependencies": {
    "express": "^4.15.2",
    "socket.io": "^2.0.4",
    "request": "latest"
  }
}
```

If done, save this file. Now, you can install all required libraries. You can type this command in the project folder. Make sure your computer is connected to the Internet:

```
$ npm install
```

Now you can write `index.js` for the application. This program will open a port 3000 to listen for HTTP requests. The program also requests sensor data from the WebSense node every three seconds. You can type these scripts for `index.js`:

```
var express = require('express');
var request = require('request');
var app = express();
var http = require('http').Server(app);
var io = require('socket.io')(http);

app.use(express.static('public'));


app.get('/', function(req, res){
    res.sendFile(__dirname + '/index.html');
});
```

```
io.on('connection', function(socket) {
    var dataPusher = setInterval(function () {
        request.get('http://[fd00::212:4b00:797:6083]/',function
        (err,res,body){
            if(err){
                console.log(err);
                return;
            }
            var obj = JSON.parse(body);
            socket.broadcast.emit('data', obj.temp);
        });

    }, 3000);

    socket.on('disconnect', function() {
        console.log('closing');
    });
});

http.listen(3000, function(){
    console.log('listening on *:3000');
});
```

You should change the IPv6 address of the WebSense node.

Next, we create `index.html` in the `<project>/public` folder. This program will communicate with the RESTful server though JSON communication. If the program receives sensor data, it will be stored into an array.

Then, the program will create a graphic for visualizing sensor data. You can type theses scripts for `index.html`:

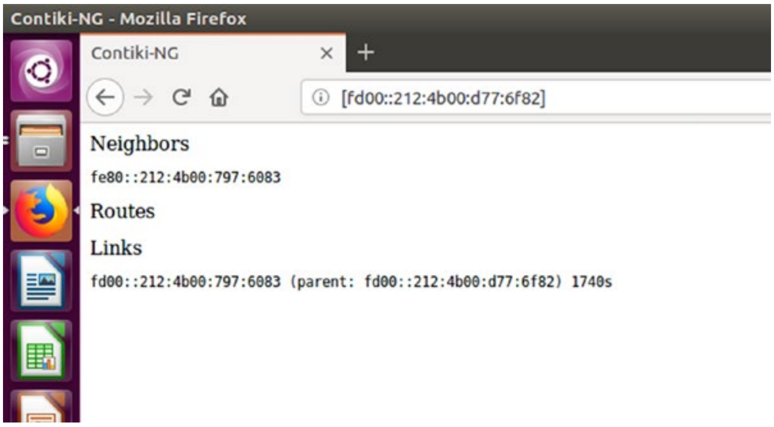
```
<html>
<head>
    <meta http-equiv="Content-Type" content="text/html;
    charset=utf-8">
    <title>Visualizing Real-Time Sensor Data</title>
    <script language="javascript" type="text/javascript"
    src="/js/jquery-3.2.1.js"></script>
    <script language="javascript" type="text/javascript"
    src="/js/jquery.flot.js"></script>
    <script src="/socket.io/socket.io.js"></script>
    <script language="javascript" type="text/javascript">
        var socket = io.connect();
        var items = [];
        var counter = 0;
        socket.on('data', function (data) {
            items.push([counter, data]);
            counter = counter + 1;
            if (items.length > 20)
                items.shift();
            $.plot($("#placeholder"), [items]);
        });
    </script>

</head>
<body>
<h1>Real-Time Sensor Data Visualization</h1>
<br>
<div id="placeholder" style="width:600px;height:300px;"></div>
</body>
</html>
```

Testing the Demo

Ensure the programs for the motes are already deployed. Now you can run the RESTful server by typing this command:

```
$ node index.js
```

Firstly, we open a browser and navigate to the IPv6 address of the 6LoWPAN router. You should see the IPv6 addresses from the motes as shown in Figure 6-48.



Neighbors

```
fe80::212:4b00:797:6083
```

Routes

Links

```
fd00::212:4b00:797:6083 (parent: fd00::212:4b00:d77:6f82) 1740s
```

Figure 6-48. *Accessing web server from RPL border router mote*

After the RESTful server is running, you can test it by opening a browser. Navigate to the RESTful server's IP address with port 3000. For instance, you can open a browser on your local server and navigate to `http://localhost:3000`. You should see sensor data visualization. You can see this in Figure 6-49.

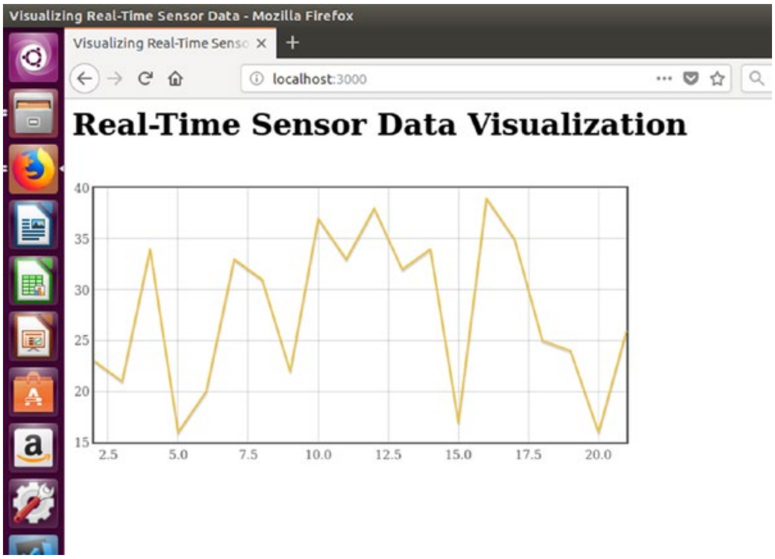

Visualizing Real-Time Sensor Data - Mozilla Firefox
Visualizing Real-Time Senso
localhost:3000
Real-Time Sensor Data Visualization
40
35
30
25
20
15
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0

Figure 6-49. *Accessing WebSense application using a browser*

What's next?

You can create more sensor sources in different sensor types from several motes. Then, you can modify sensor data visualization to cover multiple sensor types.

Summary

We have explored Contiki-NG networking. We have learned about routing models in Contiki-NG. Furthermore, we have worked with IPv6 multicast. We also implemented 6LoWPAN on physical motes and COOJA simulations. Last, we build sensor data visualization in real-time from a physical mote.

In the next chapter, we will learn to work with storage management in Contiki-NG.

CHAPTER 7

Storage

Wireless Sensor Networks (WSN) are designed to perform sensing and then send the sensing data to a gateway or a certain server. You probably will want to perform some computations before sending the data. These computations involve some parameters that should be kept by WSN devices. Keeping data in a WSN device requires storage. In this chapter, we will learn how to work with storage in Contiki-NG.

The following is a list of topics that will be covered in this chapter:

- Storage models in Contiki-NG
- Working with local storage
- Working with Coffee file system
- Contiki-NG and MySQL

Storage Models in Contiki-NG

Contiki-NG is designed for small devices with optimized computation. You will probably need to store data from your project, such as sensor data or program parameters. These data can be persistent data. The data also is used to analyze and investigate something from your project.

Storage models in Contiki-NG are shown in Figure 7-1. We define a storage model of Contiki-NG based on where the data will be stored. We can put our data in internal or external storage. Internal storage is a part of the internal MCU storage, such as ROM and RAM. Otherwise, we can extend our Contiki-NG storage by adding external storage.

From Figure 7-1, we can see that external storage comes in two models: local storage and external storage. We can attach any external storage, such as SD card and micro SD card, to a Contiki-NG mote. Then, we can save our data into these storage devices through SPI or I2C protocols. Remote storage can be represented as network storage. This means Contiki-NG will save data to a remote data server, such as MySQL, PostgreSQL, SQL Server, or Oracle, via a network protocol.

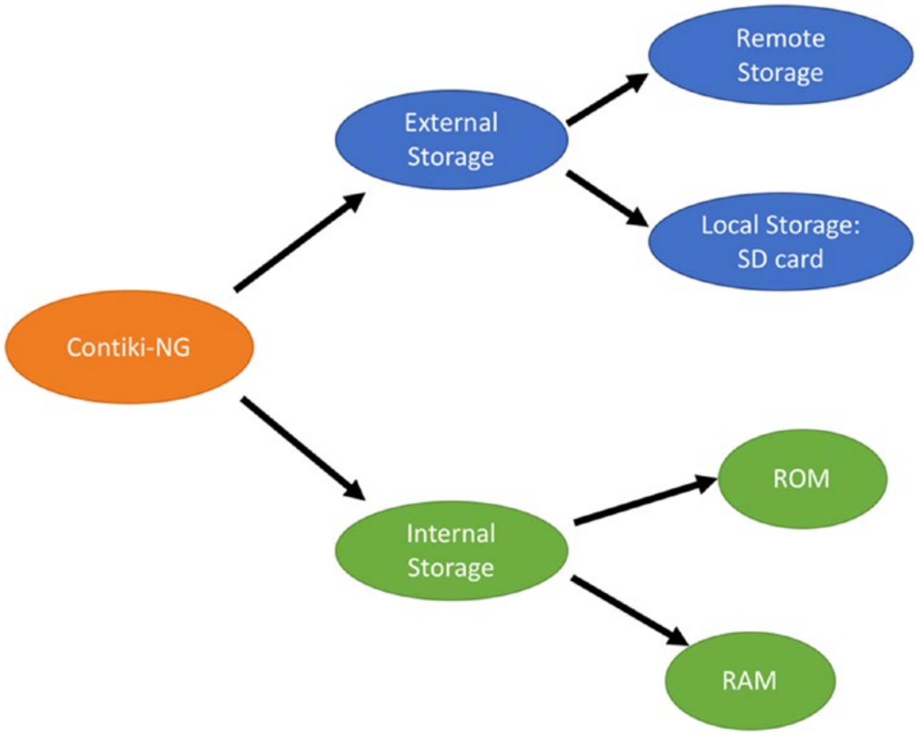


Figure 7-1. *Storage models in Contiki-NG*

Each storage model in Contiki-NG has advantages and disadvantages. You can choose which model based on your needs. You can see the storage model comparison table in Table 7-1.

Table 7-1. *Comparing Storage Mmodels in Contiki-NG*

Features	ROM	RAM	Local Storage	Remote Storage
Can read?	Yes	Yes	Yes	Yes
Can write?	No	Yes	Yes	Yes
Access speed	Fast	Fast	Moderate	Moderate/Slow
Access protocols	Check MCU datasheet from the mote	Check MCU datasheet from the mote	SPI, I2C	HTTP, RESTful, TCP

ROM and RAM provide good speed for reading and writing data, but not all MCU devices have large storage sizes for the ROM and RAM. A local storage approach is a good choice if you plan to perform logging for system evaluation. The remote storage option is best if you need to perform data consolidation. You can do data analysis and predictive analytics from your collected data.

Working with Local Storage

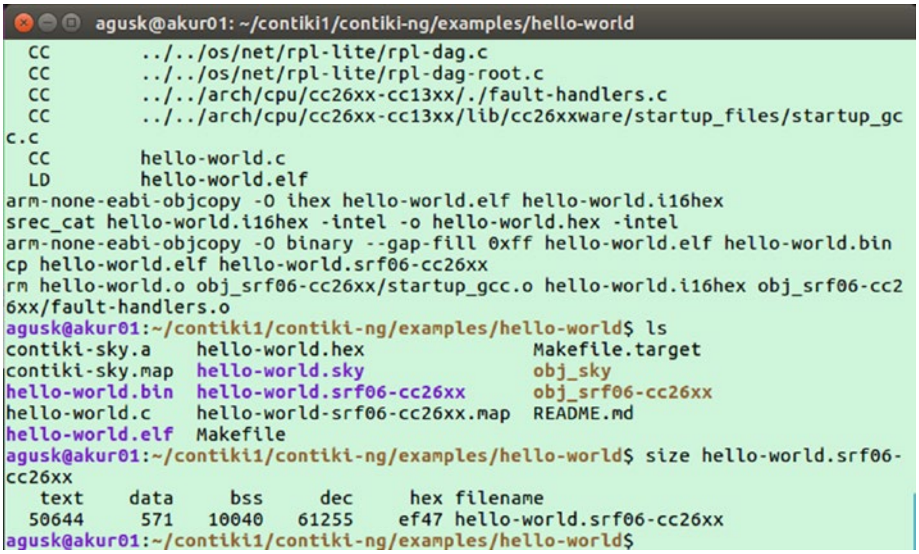
In this section, we will learn how to work with local storage in Contiki-NG. We will review how a program uses resources in RAM and ROM via Contiki-NG. For instance, we want to analyze the hello-world program from Contiki-NG samples. I will test it with targeting on LaunchPad CC2650. First, we compile the hello-world program. You can type these commands:

```
$ make TARGET=srf06-cc26xx BOARD=launchpad/cc2650
$ make TARGET=srf06-cc26xx BOARD=launchpad/cc2650 savetarget
```

Then, we analyze resource allocation for the hello-world program using this command:

```
$ size hello-world.srf06-cc26xx
```

You can see the program output in Figure 7-2. `text` shows the size of the code section in bytes that will be stored in ROM. `data` and `bss` show sections that contain variables and will be stored in RAM. From Figure 7-2, we can see that the hello-world program fits in ROM with its 50644-byte size.



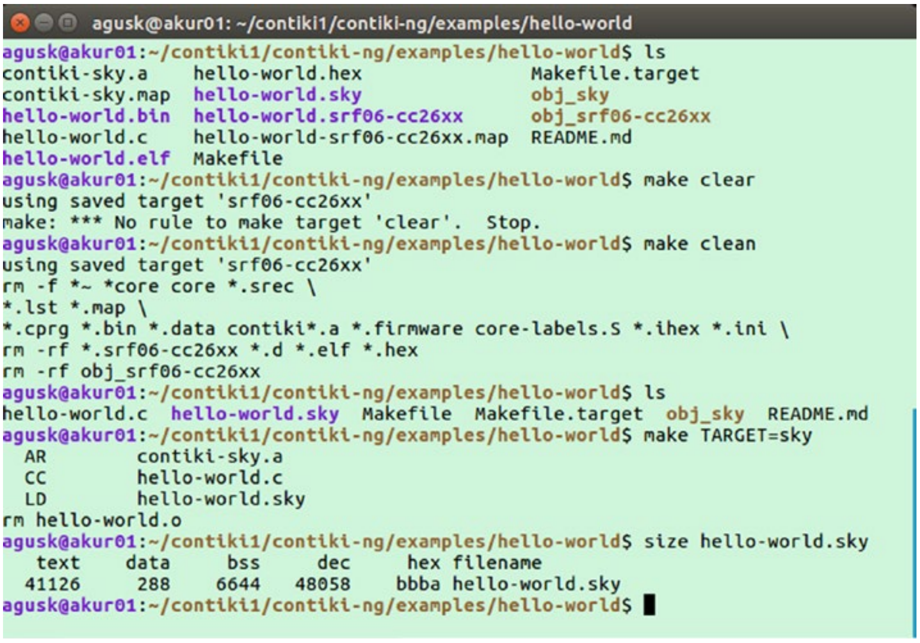
```
agusk@akur01: ~/contiki1/contiki-ng/examples/hello-world
  CC        ../../os/net/rpl-lite/rpl-dag.c
  CC        ../../os/net/rpl-lite/rpl-dag-root.c
  CC        ../../arch/cpu/cc26xx-cc13xx/./fault-handlers.c
  CC        ../../arch/cpu/cc26xx-cc13xx/lib/cc26xxware/startup_files/startup_gc
c.c
  CC        hello-world.c
  LD        hello-world.elf
arm-none-eabi-objcopy -O ihex hello-world.elf hello-world.i16hex
srec_cat hello-world.i16hex -intel -o hello-world.hex -intel
arm-none-eabi-objcopy -O binary --gap-fill 0xff hello-world.elf hello-world.bin
cp hello-world.elf hello-world.srf06-cc26xx
rm hello-world.o obj_srf06-cc26xx/startup_gcc.o hello-world.i16hex obj_srf06-cc2
6xx/fault-handlers.o
agusk@akur01:~/contiki1/contiki-ng/examples/hello-world$ ls
contiki-sky.a    hello-world.hex              Makefile.target
contiki-sky.map  hello-world.sky              obj_sky
hello-world.bin  hello-world.srf06-cc26xx     obj_srf06-cc26xx
hello-world.c    hello-world-srf06-cc26xx.map README.md
hello-world.elf  Makefile
agusk@akur01:~/contiki1/contiki-ng/examples/hello-world$ size hello-world.srf06-
cc26xx
   text    data     bss     dec     hex filename
  50644     571   10040   61255    ef47 hello-world.srf06-cc26xx
agusk@akur01:~/contiki1/contiki-ng/examples/hello-world$
```

Figure 7-2. *Analyzing binary program on Contiki-NG with LaunchPad CC2650 platform*

If you use the Sky platform, you can verify the hello-world program size with a similar approach. You can type these commands:

```
$ make TARGET=sky
$ make TARGET=sky savetarget
$ size hello-world.sky
```

After executing those commands, you can see the program output in Figure 7-3. This program reserves 41126 bytes in ROM.



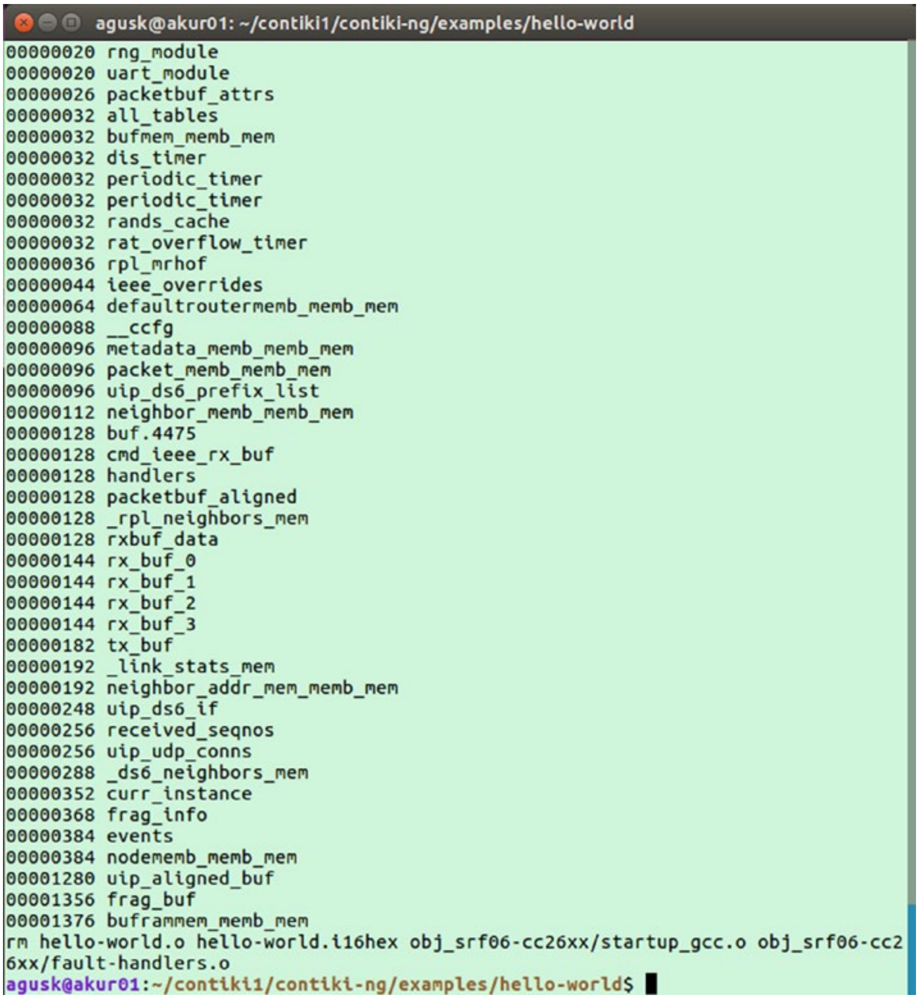
```
agusk@akur01: ~/contiki1/contiki-ng/examples/hello-world
agusk@akur01:~/contiki1/contiki-ng/examples/hello-world$ ls
contiki-sky.a    hello-world.hex              Makefile.target
contiki-sky.map  hello-world.sky              obj_sky
hello-world.bin  hello-world.srf06-cc26xx     obj_srf06-cc26xx
hello-world.c    hello-world-srf06-cc26xx.map README.md
hello-world.elf  Makefile
agusk@akur01:~/contiki1/contiki-ng/examples/hello-world$ make clear
using saved target 'srf06-cc26xx'
make: *** No rule to make target 'clear'.  Stop.
agusk@akur01:~/contiki1/contiki-ng/examples/hello-world$ make clean
using saved target 'srf06-cc26xx'
rm -f *~ *core core *.srec \
*.lst *.map \
*.cprg *.bin *.data contiki*.a *.firmware core-labels.S *.ihex *.ini \
rm -rf *.srf06-cc26xx *.d *.elf *.hex
rm -rf obj_srf06-cc26xx
agusk@akur01:~/contiki1/contiki-ng/examples/hello-world$ ls
hello-world.c  hello-world.sky  Makefile  Makefile.target  obj_sky  README.md
agusk@akur01:~/contiki1/contiki-ng/examples/hello-world$ make TARGET=sky
  AR        contiki-sky.a
  CC        hello-world.c
  LD        hello-world.sky
rm hello-world.o
agusk@akur01:~/contiki1/contiki-ng/examples/hello-world$ size hello-world.sky
   text    data     bss     dec     hex filename
  41126     288    6644   48058    bbba hello-world.sky
agusk@akur01:~/contiki1/contiki-ng/examples/hello-world$
```

Figure 7-3. *Analyzing binary program on Contiki-NG with Sky platform*

If you want to get a detail of the program address usage from RAM, call this command:

```
$ make hello-world.ramprof
```

After it has been executed, you should see a list of program addresses in RAM. A sample of program output for the LaunchPad CC2650 board can be seen in Figure 7-4. For instance, the events program is fitted on 00000384.



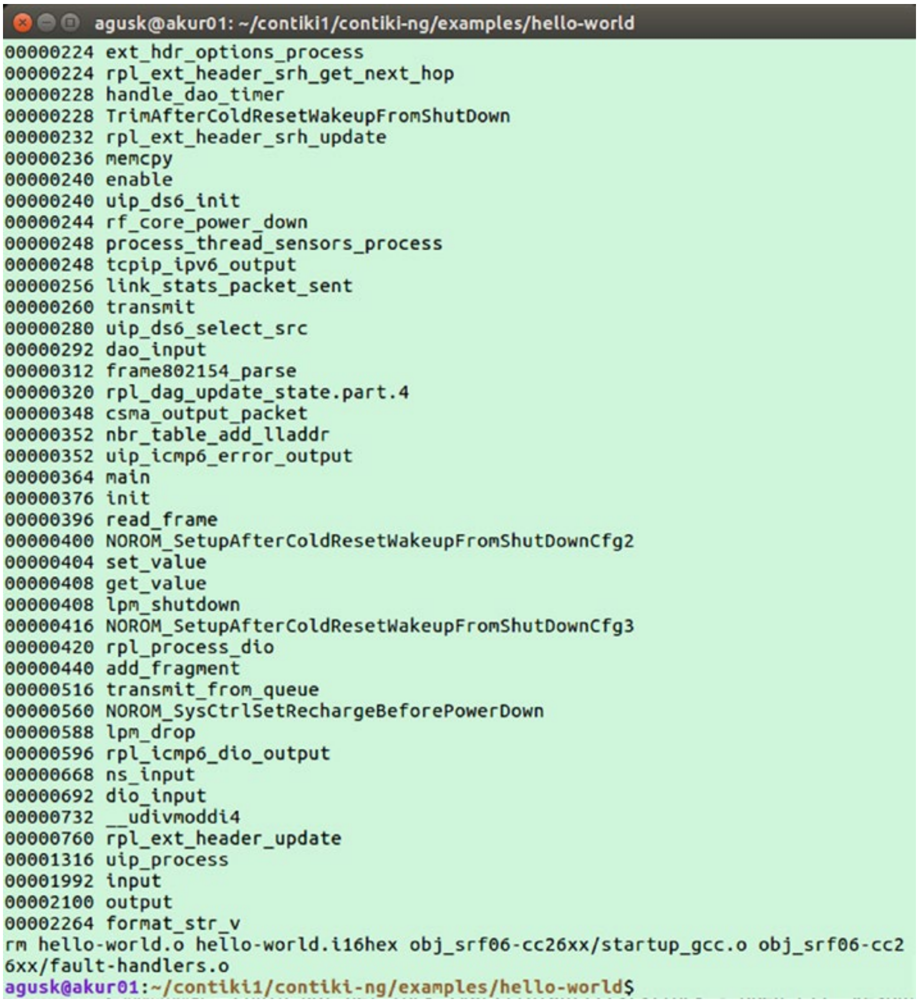
```
agusk@akur01: ~/contiki1/contiki-ng/examples/hello-world
00000020 rng_module
00000020 uart_module
00000026 packetbuf_attrs
00000032 all_tables
00000032 bufmem_memb_mem
00000032 dis_timer
00000032 periodic_timer
00000032 periodic_timer
00000032 rands_cache
00000032 rat_overflow_timer
00000036 rpl_mrhof
00000044 ieee_overrides
00000064 defaultroutermemb_memb_mem
00000088 __ccfg
00000096 metadata_memb_memb_mem
00000096 packet_memb_memb_mem
00000096 uip_ds6_prefix_list
00000112 neighbor_memb_memb_mem
00000128 buf.4475
00000128 cmd_ieee_rx_buf
00000128 handlers
00000128 packetbuf_aligned
00000128 _rpl_neighbors_mem
00000128 rxbuf_data
00000144 rx_buf_0
00000144 rx_buf_1
00000144 rx_buf_2
00000144 rx_buf_3
00000182 tx_buf
00000192 _link_stats_mem
00000192 neighbor_addr_mem_memb_mem
00000248 uip_ds6_if
00000256 received_seqnos
00000256 uip_udp_conns
00000288 _ds6_neighbors_mem
00000352 curr_instance
00000368 frag_info
00000384 events
00000384 nodememb_memb_mem
00001280 uip_aligned_buf
00001356 frag_buf
00001376 buframmem_memb_mem
rm hello-world.o hello-world.i16hex obj_srf06-cc26xx/startup_gcc.o obj_srf06-cc2
6xx/fault-handlers.o
agusk@akur01:~/contiki1/contiki-ng/examples/hello-world$ 
```

Figure 7-4. *A list of symbol program sizes on Contiki-NG RAM*

We also can analyze program addresses in ROM from our program. You can type this command from the hello-world program:

```
$ make hello-world.flashprof
```

You should see a list of program addresses. A program output can be seen in Figure 7-5 for the LaunchPad CC2650 board.



```
agusk@akur01: ~/contiki1/contiki-ng/examples/hello-world
00000224 ext_hdr_options_process
00000224 rpl_ext_header_srh_get_next_hop
00000228 handle_dao_timer
00000228 TrimAfterColdResetWakeupFromShutDown
00000232 rpl_ext_header_srh_update
00000236 memcpy
00000240 enable
00000240 uip_ds6_init
00000244 rf_core_power_down
00000248 process_thread_sensors_process
00000248 tcpip_ipv6_output
00000256 link_stats_packet_sent
00000260 transmit
00000280 uip_ds6_select_src
00000292 dao_input
00000312 frame802154_parse
00000320 rpl_dag_update_state.part.4
00000348 csma_output_packet
00000352 nbr_table_add_lladdr
00000352 uip_icmp6_error_output
00000364 main
00000376 init
00000396 read_frame
00000400 NOROM_SetupAfterColdResetWakeupFromShutDownCfg2
00000404 set_value
00000408 get_value
00000408 lpm_shutdown
00000416 NOROM_SetupAfterColdResetWakeupFromShutDownCfg3
00000420 rpl_process_dio
00000440 add_fragment
00000516 transmit_from_queue
00000560 NOROM_SysCtrlSetRechargeBeforePowerDown
00000588 lpm_drop
00000596 rpl_icmp6_dio_output
00000668 ns_input
00000692 dio_input
00000732 __udivmoddi4
00000760 rpl_ext_header_update
00001316 uip_process
00001992 input
00002100 output
00002264 format_str_v
rm hello-world.o hello-world.i16hex obj_srf06-cc26xx/startup_gcc.o obj_srf06-cc2
6xx/fault-handlers.o
agusk@akur01:~/contiki1/contiki-ng/examples/hello-world$
```

Figure 7-5. *A list of symbol program sizes on Contiki-NG ROM*

Coffee: File System in Contiki-NG

Coffee is one type of file system implementation in Contiki-NG. Technically, Coffee is designed for making a virtual file system on a RAM stack of Contiki-NG. We can find the `Coffee` library in the

<contiki-ng-root>/os/storage/cfs/ folder. There are three files: cfs.h, cfs-coffee.h, and cfs-coffee.c. This module implements basic operations for reading and writing files, like the POSIX file API.

Since Coffee uses RAM as storage, it's a temporary storage option. You can use this storage to store your temporary data, such as computation parameters and a counter number. You should be aware that Coffee data is deleted when the Contiki-NG mote is restarting or stopping.

We access a file through the Coffee File System (CFS) library. This library API interface can be found in the <contiki-ng-root>/os/storage/cfs/cfs.h file. You can see a list of functions from the cfs.h file in Table 7-2.

Table 7-2. *CFS Functions from cfs.h Header File*

Functions	Description
int cfs_open(const char *name, int flags)	Open a file
void cfs_close(int fd)	Close a file
int cfs_read(int fd, void *buf, unsigned int len)	Read data from a file
int cfs_write(int fd, const void *buf, unsigned int len)	Write data to a file
cfs_offset_t cfs_seek(int fd, cfs_offset_t offset, int whence)	Move to a specific position in a file
int cfs_remove(const char *name)	Remove a file
int cfs_opendir(struct cfs_dir *dirp, const char *name)	Open a directory
int cfs_readdir(struct cfs_dir *dirp, struct cfs_dirent *dirent)	Read a directory entry
void cfs_closedir(struct cfs_dir *dirp)	Close a directory

To work with CFS, your project should include the `cfs` library. You can add it to the `Makefile` file. Add this script:

```
MODULES += os/storage/cfs
```

For this demo, we will create a simple program to show how to work with CFS on Contiki-NG. We will create a file and write data to that file. Next, we will open a file and read data from the file. In this demo, I will use the Sky platform.

First, create a folder, called `file-cfs-demo.` You can add two files, `Makefile` and `file-cfs-demo.c`. Configure the project in `Makefile`. You can write these scripts for the `Makefile` file:

```
CONTIKI_PROJECT = file-cfs-demo

MODULES += os/storage/cfs
CONTIKI = ../..
all: $(CONTIKI_PROJECT)

include $(CONTIKI)/Makefile.include
```

You probably need to change the `CONTIKI` value to your Contiki-NG project directory. Now, you can write the program for the `file-cfs-demo.c` file. Write the following code skeleton from our demo:

```
#include "contiki.h"
#include "cfs/cfs.h"
#include "cfs/cfs-coffee.h"
#include "lib/crc16.h"
#include "lib/random.h"

#include <stdio.h>
#include <string.h>
```

```
PROCESS(coffee_demo_process, "CFS/Coffee demo process");
AUTOSTART_PROCESSES(&coffee_demo_process);

static void
coffee_file_demo(void)
{
  // coffee file demo

}
PROCESS_THREAD(coffee_demo_process, ev, data)
{
  PROCESS_BEGIN();

  printf("Coffee file demo...\n");
  coffee_file_demo();

  PROCESS_END();
}
```

This program will run the `coffee_file_demo()` function on the main program. We will implement the CFS demo on that function.

First, we initialize program variables, including file descriptors for opening and reading file handlers:

```
  int wfd, rfd, afd;
  unsigned char buf[32];
  int r;

  wfd = rfd = afd = -1;
```

We set all buffer data with certain values:

```
  for(r = 0; r < sizeof(buf); r++) {
    buf[r] = r + 4;
  }
```

We open a file, `mycfs`, by calling the `cfs_open()` function:

```
printf("opening file for writing\n");
wfd = cfs_open("mycfs", CFS_WRITE);
if(wfd < 0) {
  printf("Error creating file\n");
  return;
}
```

Next, we write data to a file by calling the `cfs_write()` function. We also print all data to Terminal so you can see the data on the Contiki-NG Terminal:

```
printf("writing data into file\n");
printf("write: ");
for(r = 0; r < sizeof(buf); r++) {
  printf("%d ", buf[r]);
}
printf("\n");
r = cfs_write(wfd, buf, sizeof(buf));
if(r < 0) {
  printf("Error writing data into file\n");
  cfs_close(wfd);
  cfs_remove("mycfs");
  return;
} else if(r < sizeof(buf)) {
  printf("Error writing data into file\n");
  cfs_close(wfd);
  cfs_remove("mycfs");
  return;
}
```

After writing the data, we should close the opened file:

```
printf("close file\n");
cfs_close(wfd);
```

We have created a file and written data into the file. We will continue to read data from a file. We use a different file descriptor that we have declared.

We open a file and read data from the file using the `cfs_read()` function:

```
printf("opening file for reading\n");
rfd = cfs_open("mycfs", CFS_READ);
if(rfd < 0) {
  printf("Error opening file\n");
  cfs_remove("mycfs");
  return;
}
printf("reading data\n");
memset(buf, 0, sizeof(buf));
r = cfs_read(rfd, buf, sizeof(buf));
if(r < 0) {
  printf("Error reading file\n");
  cfs_close(rfd);
  cfs_remove("mycfs");
  return;
}
```

After reading the data, we print it to Terminal. Then, we close that file:

```
printf("read: ");
for(r = 0; r < sizeof(buf); r++) {
  printf("%d ", buf[r]);
}
printf("\n");

printf("close file\n");
cfs_close(rfd);
```

Last, we delete our created file, since Contiki-NG has limited resources.

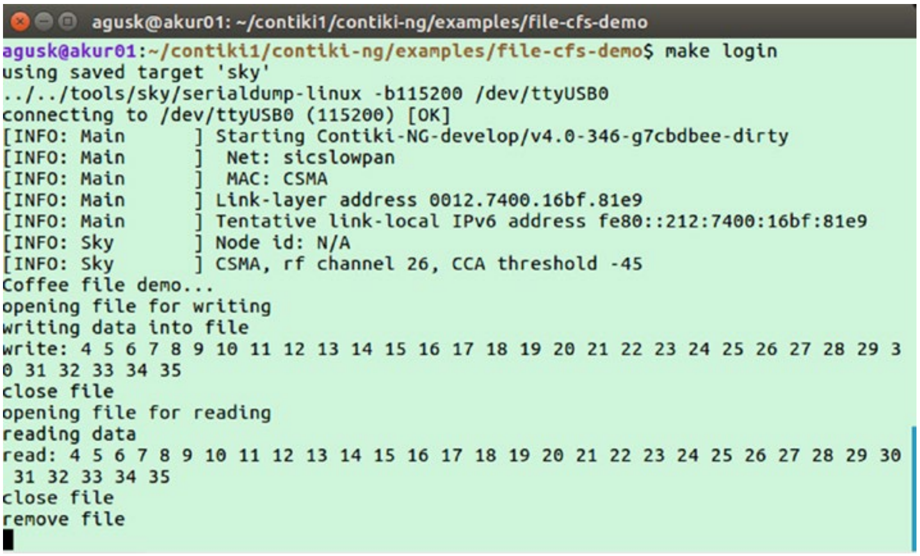
Save this program. Then, you can compile and flash it to your Contiki-NG board. For instance, I flash this program to my Sky board:

```
$ make TARGET=sky
$ make TARGET=sky savetarget
$ make file-cfs-demo.upload
```

Now, you can perform monitoring on the target board. You can type this command:

```
$ make login
```

You should see the program output in Terminal. If not, you can reset your board. A sample of the program output can be seen in Figure 7-6.



```
agusk@akur01: ~/contiki1/contiki-ng/examples/file-cfs-demo
agusk@akur01:~/contiki1/contiki-ng/examples/file-cfs-demo$ make login
using saved target 'sky'
../../tools/sky/serialdump-linux -b115200 /dev/ttyUSB0
connecting to /dev/ttyUSB0 (115200) [OK]
[INFO: Main      ] Starting Contiki-NG-develop/v4.0-346-g7cbdbee-dirty
[INFO: Main      ]  Net: sicslowpan
[INFO: Main      ]  MAC: CSMA
[INFO: Main      ] Link-layer address 0012.7400.16bf.81e9
[INFO: Main      ] Tentative link-local IPv6 address fe80::212:7400:16bf:81e9
[INFO: Sky       ] Node id: N/A
[INFO: Sky       ] CSMA, rf channel 26, CCA threshold -45
Coffee file demo...
opening file for writing
writing data into file
write: 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 3
0 31 32 33 34 35
close file
opening file for reading
reading data
read: 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
 31 32 33 34 35
close file
remove file
```

Figure 7-6. *Coffee file system demo on Sky platform*

Demo: Contiki-NG and MySQL

In this section, we will build a Contiki-NG program that interacts with MySQL. The object of the demo is to show how Contiki-NG can store sensor data in a DBMS (Database Management System) system.

For this demo, we choose MySQL for the DBMS. In general, we will build our demo implementation as shown in Figure 7-7.

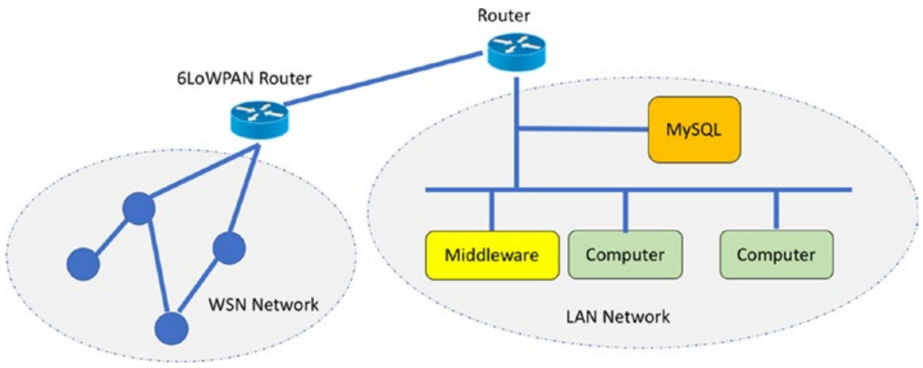


Figure 7-7. *A design for Contiki-NG and MySQL demo*

All sensor devices are attached to Contiki-NG motes that are deployed on a private WSN network. To communicate with an outside network, we will use a 6LoWPAN router. You learned about the 6LoWPAN router in Chapter 6.

We also implement middleware that works as a gateway. The middleware retrieves sensor data from Contiki-NG. Then, it stores sensor data into MySQL. We will develop this middleware using Node.js. Data communication between a middleware application and Contiki-NG uses JSON.

This demo needs two Contiki-NG motes at least. One mote will be used as the 6LoWPAN router. The rest will be deployed as sensor programs. In this demo, we will perform some tasks as follows:

- Design and build database
- Build 6LoWPAN router

- Develop Contiki-NG sensor application
- Develop Middleware application

We implement each task in the next sections.

Preparation

We need to prepare our demo. First, we install MySQL on a computer that is connected to the same network. For Ubuntu/Debian, you can install MySQL by typing these commands in Terminal:

```
$ sudo apt-get update
$ sudo apt-get install mysql-server
$ mysql_secure_installation
```

Another option is to download MySQL for your platform from https://www.mysql.com/downloads/.

You also should install MySQL Workbench. This is an optional task. MySQL Workbench is designed to build a design database and manage MySQL Server. You can install MySQL Workbench by typing this command:

```
$ sudo apt install mysql-workbench
```

Design a Database

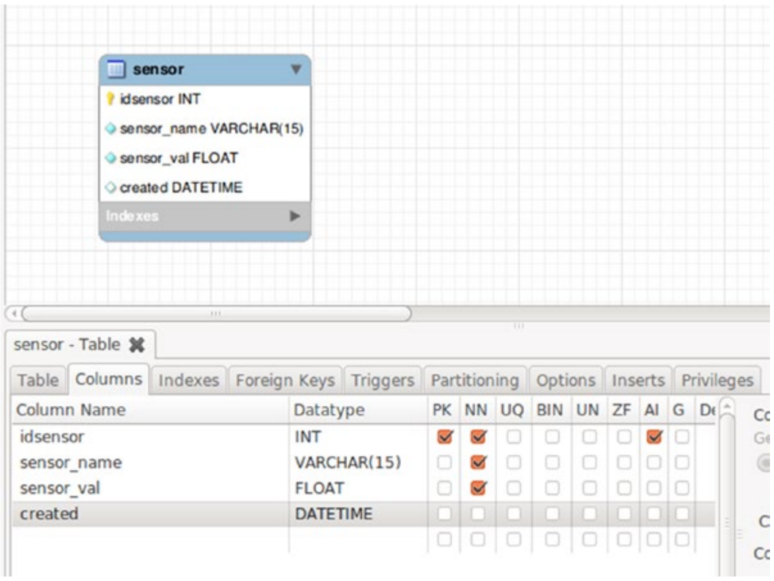
In this section, we will build a database on MySQL. We create a database, called `contiki-ng-db`. Furthermore, we should create a table to store the sensor data.

We can create the database and table using MySQL Workbench. Create a table on the database, called `sensor`. You can create a table with the scheme that is shown in Table 7-3.

Table 7-3. *Designing a Table for Demo*

Table Field	Properties
idsensor	Datatype: INT Checked: Primary Key (PK), Not Null (NN), Auto Increment (AI)
sensor_name	Datatype: VARCHAR (15) Checked: Not Null (NN)
sensor_val	Datatype: FLOAT Checked: Not Null (NN)
created	Datatype: DATETIME

This design is shown in Figure 7-8.



Column Name	Datatype	PK	NN	UQ	BIN	UN	ZF	AI	G
idsensor	INT	✓	✓					✓	
sensor_name	VARCHAR(15)		✓						
sensor_val	FLOAT		✓						
created	DATETIME								

Figure 7-8. *Database design for the project*

Once done, you should deploy the database and table designs to MySQL Server. You also must configure security access, creating one user to access the database that will used for your application.

Build a 6LoWPAN Router

In this section, we will develop programs for Contiki-NG, using one Contiki-NG mote as a 6LoWPAN router. You already learned about that topic in Chapter 6. You can run the program sample from the `<contiki-ng>/examples/rpl-border-router/` folder.

Compile this project and flash it to one of the Contiki-NG motes. In this demo, I use a LaunchPad CC2560 board for testing. After deploying it to the mote, you can build the 6LoWPAN router by typing this command in Terminal:

```
$ make TARGET=srf06-cc26xx BOARD=launchpad/cc2650 connect-router
```

You can change the `TARGET` and `BOARD` if you use a different Contiki-NG platform.

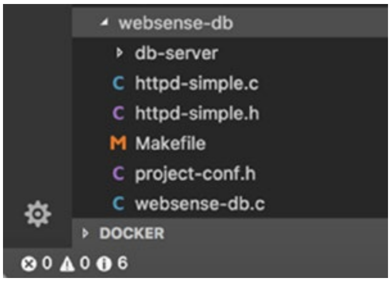
Develop a Contiki-NG Sensor Application

We build sensor applications to perform sensing. For simple problems, I generate random values for the temperature and humidity sensors. You can implement your own real sensors for your project.

We will modify the websense program from the previous chapter. We call this project websense-db. You can see the project structure in Figure 7-9. We construct two sensor data: temperature and humidity. In the `websense-db.c` file, we add our sensor data in the `generate_routes()` process:

```
static
PT_THREAD(generate_routes(struct httpd_state *s))
{
  char buff[35];

  PSOCK_BEGIN(&s->sout);
  //SEND_STRING(&s->sout, TOP);
  int temperature = 15 + rand() % 25;
  int humidity = 80 + rand() % 10;

  sprintf(buff,"{\"temp\":%u,\"hum\":%u}", temperature, humidity);
  printf("send json to requester\n");

  SEND_STRING(&s->sout, buff);
  //SEND_STRING(&s->sout, BOTTOM);

  PSOCK_END(&s->sout);
}
```

You can modify this code to replace the random values with real results from your sensor readings.



websense-db
db-server
httpd-simple.c
httpd-simple.h
Makefile
project-conf.h
websense-db.c
DOCKER
0 0 6

Figure 7-9. *Project structure of websense-db*

Develop Middleware Application

This middleware application has the responsibility of retrieving sensor data from Contiki-NG and then sending these data to MySQL Server. This application will be developed using Node.js. Set up the Node.js development environment by downloading it from `http://nodejs.org`.

To access MySQL from the Node.js application, you should install the MySQL driver for Node.js. You can use the official driver from MySQL. In this demo, we will use the `mysql` library. You can see it at `https://github.com/mysqljs/mysql`.

First, we create a folder, called `sensor-db`. Then, we create a `package.json` file that consists of the required libraries for our application. You can write the following scripts to the `package.json` file:

```
{
  "name": "sensor-db",
  "version": "1.0.0",
  "description": "saving sensor data to MySQL",
  "main": "index.js",
  "scripts": {
    "test": "echo \"Error: no test specified\" && exit 1"
  },
  "author": "Agus Kurniawan",
  "dependencies": {
    "express": "^4.15.2",
    "mysql": "^2.15.0",
    "request": "latest"
  }
}
```

Save these scripts. Now, you should install all the required libraries by typing this command:

```
$ npm install
```

This action will download all declared libraries in the `package.json` file.

Next, we build the Node.js program by creating a file, `index.js`. The program will run as web server and retrieve sensor data every five seconds. First, we declare our variables and database parameters in the `index.js` file:

```
var express = require('express');
var request = require('request');
var app = express();
var http = require('http').Server(app);
var mysql      = require('mysql');
var connection = mysql.createConnection({
  host     : 'localhost',
  user     : '<user>',
  password : '<db-password>',
  database : 'contiki-ng-db'
});
```

Change MySQL database parameters such as user and password as needed.

We connect to MySQL and run a web server through an ExpressJS engine. In this case, I use a web server with port 3000. You should change it to your own port. See here:

```
connection.connect();
app.use(express.static('public'));

app.get('/', function(req, res){
    res.send('WebSense DB');
});

http.listen(3000, function(){
    console.log('listening on *:3000');
    console.log('websense db was started');
});
```

Last, we retrieve the sensor data from the Contiki-NG mote. For this demo, I set a specific IPv6 address from the Contiki-NG mote: fd00::212:4b00:797:6083. You can change it to your Contiki-NG IPv6 address.

After obtaining the sensor data, we send this data to MySQL by calling `query()`. We use a SQL statement to insert the data into the MySQL database:

```
var dataPusher = setInterval(function () {

    request.get('http://[fd00::212:4b00:797:6083]/',
    function(err,res,body){
        if(err){
            console.log(err);
            return;
        }
        var obj = JSON.parse(body);
        console.log(obj);

        connection.query({
            sql: 'INSERT INTO sensor(sensor_name,sensor_val,
            created) values(?,?,now())',
            timeout: 40000, // 40s
            values: [obj.temp,obj.hum]
        }, function (error, results, fields) {
            if(error){
                console.log(err);
                return;
            }
            console.log('inserted data to MySQL');
        });
    });

}, 5000);
```

Save all the code. We will now test our program.

Testing the Project

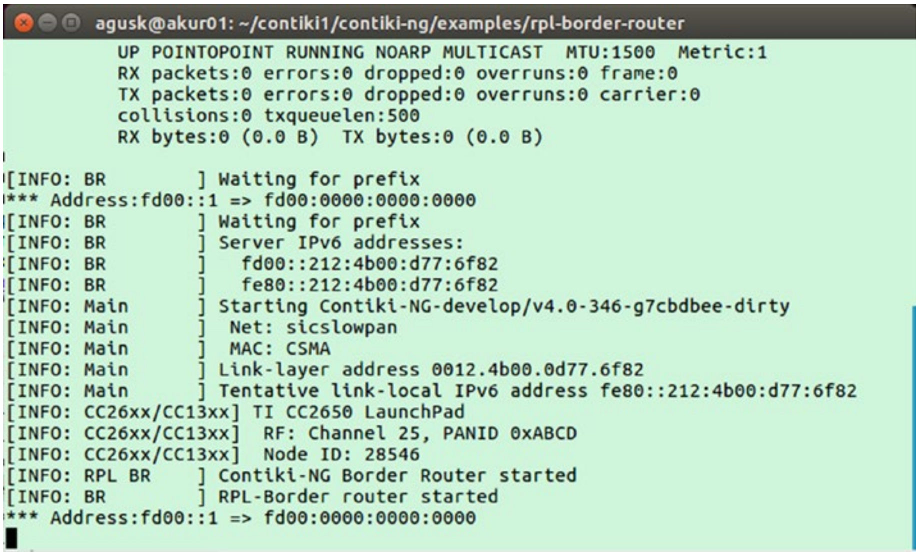
In this section, we will test our project. Make sure you have deployed the Contiki-NG program for the 6LoWPAN router and sensor mote.

First, we activate the 6LoWPAN router. Navigate to the `<contiki-ng>/examples/rpl-border-router/` folder. Then, run the 6LoWPAN router application. I run it on LaunchPad CC2650:

```
$ make TARGET=srf06-cc26xx BOARD=launchpad/cc2650 connect-router
```

You should change the target and board to your own Contiki-NG board.

After running the program, you should turn on all sensor devices on the Contiki-NG motes. You should see all neighboring Contiki-NG motes. You can see my program output from the 6LoWPAN router program in Figure 7-10.



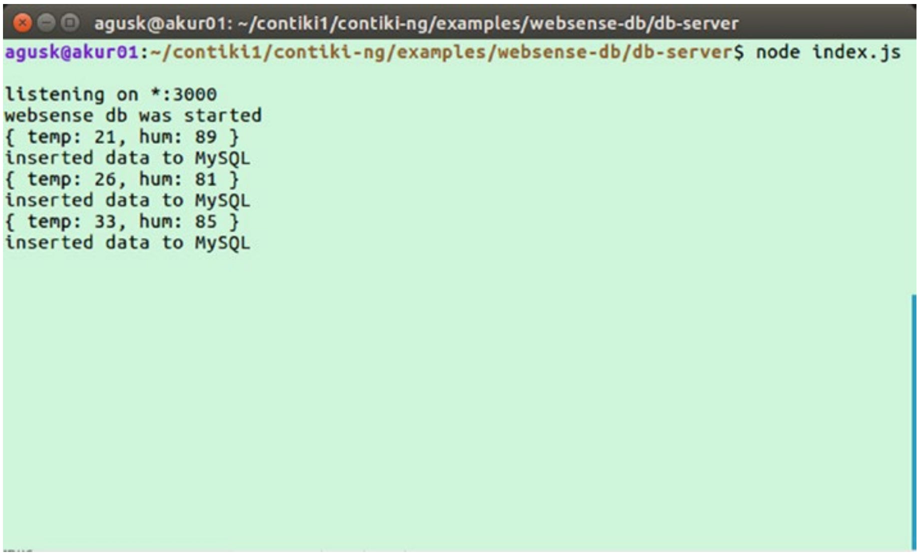
```
agusk@akur01: ~/contiki1/contiki-ng/examples/rpl-border-router
          UP POINTOPOINT RUNNING NOARP MULTICAST  MTU:1500  Metric:1
          RX packets:0 errors:0 dropped:0 overruns:0 frame:0
          TX packets:0 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:500
          RX bytes:0 (0.0 B)  TX bytes:0 (0.0 B)

[INFO: BR        ] Waiting for prefix
*** Address:fd00::1 => fd00:0000:0000:0000
[INFO: BR        ] Waiting for prefix
[INFO: BR        ] Server IPv6 addresses:
[INFO: BR        ]   fd00::212:4b00:d77:6f82
[INFO: BR        ]   fe80::212:4b00:d77:6f82
[INFO: Main      ] Starting Contiki-NG-develop/v4.0-346-g7cbdbee-dirty
[INFO: Main      ]  Net: sicslowpan
[INFO: Main      ]  MAC: CSMA
[INFO: Main      ] Link-layer address 0012.4b00.0d77.6f82
[INFO: Main      ] Tentative link-local IPv6 address fe80::212:4b00:d77:6f82
[INFO: CC26xx/CC13xx] TI CC2650 LaunchPad
[INFO: CC26xx/CC13xx]  RF: Channel 25, PANID 0xABCD
[INFO: CC26xx/CC13xx]  Node ID: 28546
[INFO: RPL BR    ] Contiki-NG Border Router started
[INFO: BR        ] RPL-Border router started
*** Address:fd00::1 => fd00:0000:0000:0000
```

Figure 7-10. *Program output from rpl-border-router application*

Now, you can run the middleware application. Open a new Terminal window and navigate to the middleware application. Then, type this command to run it:

```
$ node index.js
```

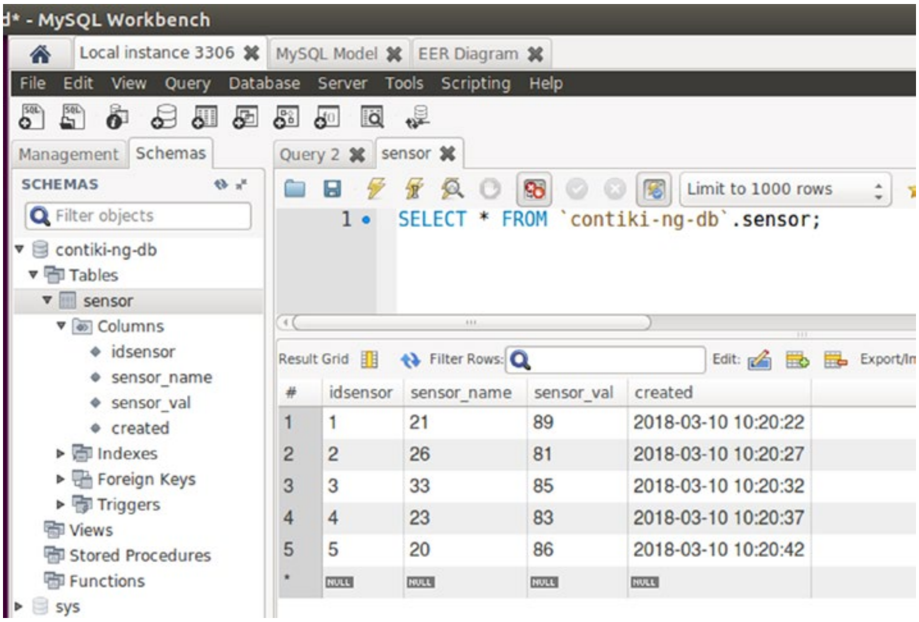
You should see sensor data from the Contiki-NG mote. Then, it is stored in the MySQL database. You can see the program output from the middleware application in Figure 7-11.



```
agusk@akur01: ~/contiki1/contiki-ng/examples/websense-db/db-server
agusk@akur01:~/contiki1/contiki-ng/examples/websense-db/db-server$ node index.js

listening on *:3000
websense db was started
{ temp: 21, hum: 89 }
inserted data to MySQL
{ temp: 26, hum: 81 }
inserted data to MySQL
{ temp: 33, hum: 85 }
inserted data to MySQL
```

Figure 7-11. *Program output from middleware application*

You also can verify the sensor data in MySQL. Open MySQL Workbench. You should see all sensor data, as in Figure 7-12.



```
SELECT * FROM `contiki-ng-db`.sensor;
```

#	idsensor	sensor_name	sensor_val	created
1	1	21	89	2018-03-10 10:20:22
2	2	26	81	2018-03-10 10:20:27
3	3	33	85	2018-03-10 10:20:32
4	4	23	83	2018-03-10 10:20:37
5	5	20	86	2018-03-10 10:20:42
*	NULL	NULL	NULL	NULL

Figure 7-12. *Viewing data in MySQL*

Summary

We have learned how to work with storage. We also reviewed the Coffee File System (CFS) in Contiki-NG. We also tested for file manipulation using CFS. Last, we developed a project to interact with the MySQL database. We store all sensor data in the database.

In the next chapter, we will learn how to work with a Cloud platform in Contiki-NG and then interact with it.

CHAPTER 8

Contiki-NG and Cloud Server

Cloud technology provides a serverless solution to many IT problems. It eliminates the effort required to provide hardware and software. These services could be SaaS (Software as Service), PaaS (Platform as Service), or IaaS (Infrastructure as Service). In this chapter, we will integrate Contiki-NG with Cloud servers. We will also review several Cloud platforms and then try to work with them.

The following is a list of topics we will cover in this chapter:

- Introduce Cloud server
- What is Cloud computing?
- Types of Cloud-computing deployments
- Review of Cloud server platforms
- Working with Contiki-NG and Microsoft Azure
- Working with Contiki-NG and Amazon AWS

Introduce Cloud Server

If you have experience with the software development cycle, you know it starts with getting requirements and ends with developing and deploying to the production machine servers. We should provide a server location, called a data center, which is used to house the machine servers.

Building a data center is not easy. Technically, a data center has class levels. Each class level has some criteria that should be met. We also should factor in electricity usage. The physical security of the server can be one of the key factors when you build your own data center.

You can also bring your machine servers to commercial data centers. In this option, you should think about security and policy. Whether you put your machine servers in your own data center or in a commercial data center, you still should manage all software within the machines yourself. Decide whether you should manage all your machines in one location.

Cloud computing can solve some issues related to configuring and deploying applications on machines. Several Cloud-computing companies provide automatic deployment and configuration for your application. They also provide geo-location server services that enable your application to deploy only in some regions. These services can serve all requests from different locations. You can optimize customer relationships by bringing your application to a customer's local region.

Figure 8-1 shows how to deploy an application to a physical machine. You can select one of the options based on your needs. Each option has pros and cons. In this chapter, we will focus on how to integrate Contiki-NG with Cloud-computing technology. We will communicate with Cloud servers from the Contiki-NG environment.

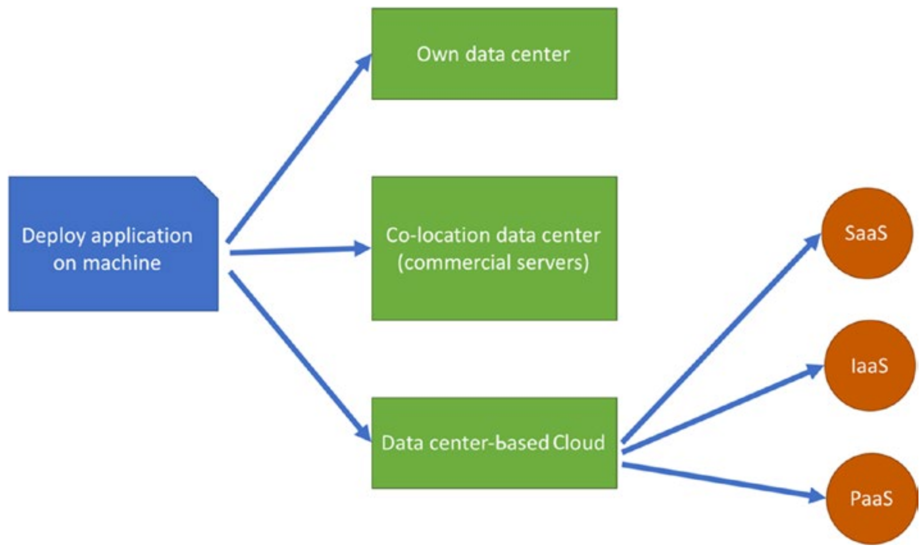

Deploy application on machine
Own data center
Co-location data center (commercial servers)
Data center-based Cloud
SaaS
IaaS
PaaS

Figure 8-1. *Application deployment strategies on physical machine*

Why Use Cloud Computing?

Cloud computing is designed to offer high flexibility for computing processes performed over the Internet. One of the big questions related to Cloud computing is why do we use it? This is a challenging question, especially for those who have already deployed an application or system on on-premises servers (local servers). For newcomers, bringing a deployment to Cloud computing is new ground.

Cloud-Computing Services

To integrate our application with Cloud computing, we should know the types of Cloud-computing services. In general, we can categorize Cloud-computing services as one of the following:

- Infrastructure-as-a-service (IaaS)
- Platform-as-a-service (PaaS)
- Software-as-a-service (SaaS)

Infrastructure-as-a-service (IaaS) provides a rent infrastructure, such as virtual machines (VMs), storage, networks, and operating systems. These providers serve your needs for machine servers, which are included in its managing dashboard. In general, you just pay for the resources you have already used.

Platform-as-a-service (PaaS) supplies an on-demand environment for developing and testing. You can create server and mobile applications without worrying about setting up or managing resource infrastructure.

Software-as-a-service (SaaS) provides all delivering software for your daily activities or certain projects. Providers usually offer subscription schemes for all delivering software. We can subscribe to and stop SaaS at any time.

Types of Cloud-Computing Deployments

To understand how to deploy Cloud computing, we should know several types of Cloud computing, such as the following:

- Public Cloud
- Private Cloud
- Hybrid Cloud

Public Cloud is a common type of Cloud deployment. You install and configure your application/platform on a provider's Cloud. Your data will be stored into their storage. Some companies probably decline to store their data on public storage servers due to compliance policies.

A private Cloud enables your solution to be deployed into local servers. Cloud providers usually provide software to build a private Cloud with their platform.

Last, a hybrid Cloud combines the public and private Cloud approaches. You can work with a hybrid Cloud to ensure your business is run well.

Review Cloud Server Platforms

In this section, we will review several Cloud platforms that provide Cloud services–based IoT (Internet of Thing). This is a brief review so you are familiar with them when we implement IoT by enabling Cloud technology.

Microsoft Azure

Microsoft is a well-known company that provides software services. We all know Microsoft products, such as Windows, Microsoft Office, and SQL Server. Now, Microsoft has expanded its software business by implementing Cloud services, called Microsoft Azure.

You can easily set up Windows servers on Microsoft Azure. All configurations are done though the Azure portal. You can access it at `https://azure.microsoft.com`. If you are a developer or a consultant with a Microsoft technology background, Microsoft Azure is a good choice to deploy Cloud computing.

Microsoft Azure is a global Cloud provider that provides Cloud services in several country regions. It can serve your needs locally.

Amazon AWS

Amazon started with its e-Commerce business. To support that business, Amazon built an IT business with Cloud technology, called Amazon AWS. Now Amazon AWS is a leading Cloud provider worldwide, available in most IT market segments. Storage and push notification services from Amazon AWS can be integrated with your mobile application. There are a lot of AWS services for your project needs. You can learn more about Amazon AWS, including registration, from the official website at `https://aws.amazon.com`.

You can integrate IoT projects with Amazon AWS. It provides a Cloud service, called AWS IoT. This service can serve your IoT needs. You can find it at `https://aws.amazon.com/iot/`.

Google Cloud

If you want to search for something online, you probably use Google. That's Google. Google Cloud provides a solution for your Cloud needs. You can find Google Cloud services at `https://Cloud.google.com`.

If you are an Android developer, Google Cloud is probably the best choice to integrate with your mobile application.

IBM Cloud

IBM has long history with servers and software. This software provides most IT services. In the Cloud-computing era, IBM now offers Cloud services, called IBM Cloud, to leverage your business. To get more information about IBM Cloud, you can visit the IBM Cloud site at `https://www.ibm.com/Cloud/`.

Comparing Features of All Global Clouds

If you are interested in Cloud services from various worldwide Cloud providers, I recommend to read this site: http://compareCloud.in. You can see a feature comparison among Cloud providers such as AWS, Azure, Google Cloud, IBM Cloud, Oracle Cloud, and Alibaba Cloud.

Connecting Contiki-NG Motes to Cloud Servers

Contiki-NG is designed for IPv6 networks. Several Contiki-NG hardware devices have network protocol capabilities to connect to Cloud servers directly. In general, we need a 6LoWPAN router as a bridge between Contiki-NG motes and a Cloud server.

In Figure 8-2, we show a simple model of how Contiki-NG motes communicate with Cloud servers. We put in a 6LoWPAN router as a bridge to all Contiki-NG motes. The 6LoWPAN router will perform request/response mapping between Contiki-NG motes and outside servers.

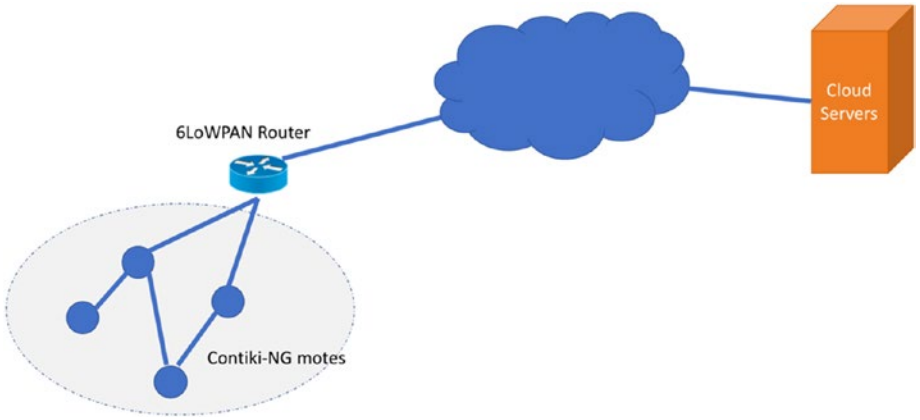


Figure 8-2. *Communicating between Contiki-NG and Cloud server*

In the next section, we will build two demos to perform a communication between Contiki-NG and Cloud servers. For these demos, we will use Microsoft Azure and Amazon AWS.

Demo 1: Contiki-NG and Microsoft Azure

This demo has the objective of showing how to communicate between Contiki-NG and Microsoft Azure. We will perform the demo described in Figure 8-3. We will develop three applications to implement this demo, as follows:

- Sensor application on Contiki-NG
- 6LoWPAN router application on Contiki-NG and computer
- Middleware application
- Azure IoT Hub application

The middleware application will retrieve sensor data from Contiki-NG and then push that data to the Azure IoT Hub. Furthermore, the Azure IoT Hub will distribute the sensor data to all subscribed devices. You can see this process in Figure 8-3.

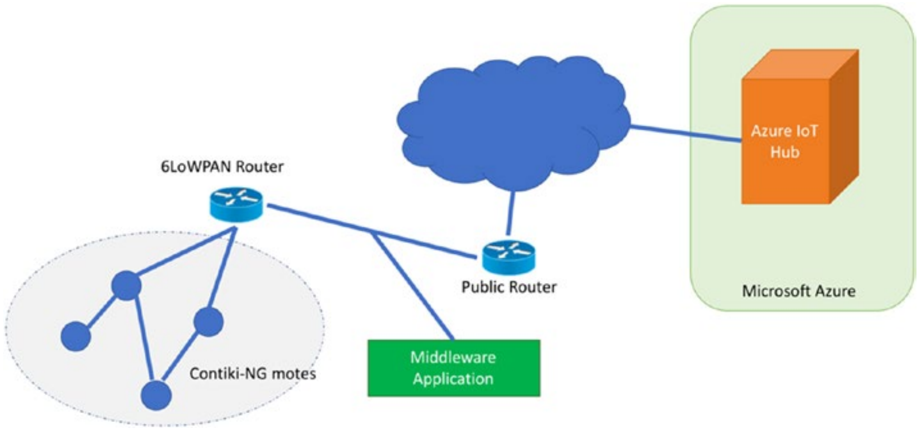


Figure 8-3. *Contiki-NG motes communicate with AWS IoT Hub*

Next, we will implement our demo by performing some tasks, as follows:

- Prepare to set up Azure IoT.
- Develop application for Contiki-NG and middleware application.
- Test all programs.

Each task will be implemented in the next section.

Preparation

Before we develop a program in which Contiki-NG will access Azure IoT Hub, we should prepare Microsoft Azure. You should have an active account for Microsoft Azure to perform this demo. To prepare our development for Azure IoT Hub, we perform the following tasks:

- Create Azure IoT Hub.
- Add a new IoT device for Azure IoT.
- Copying IoT device keys for developing program.

Each step will be performed in the next section.

Creating Azure IoT Hub

To create Azure IoT Hub, you should have an active Azure account. You can log on to `https://portal.azure.com/` with your account. On the left-hand menu on the Azure dashboard, click "IoT Hub" so you see the Azure IoT Hub dashboard, as shown in Figure 8-4.

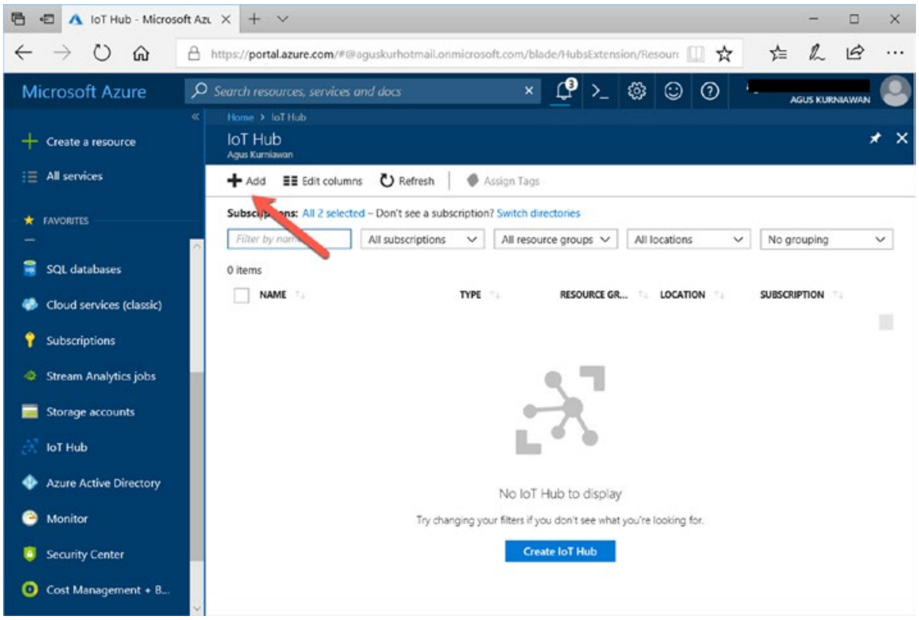
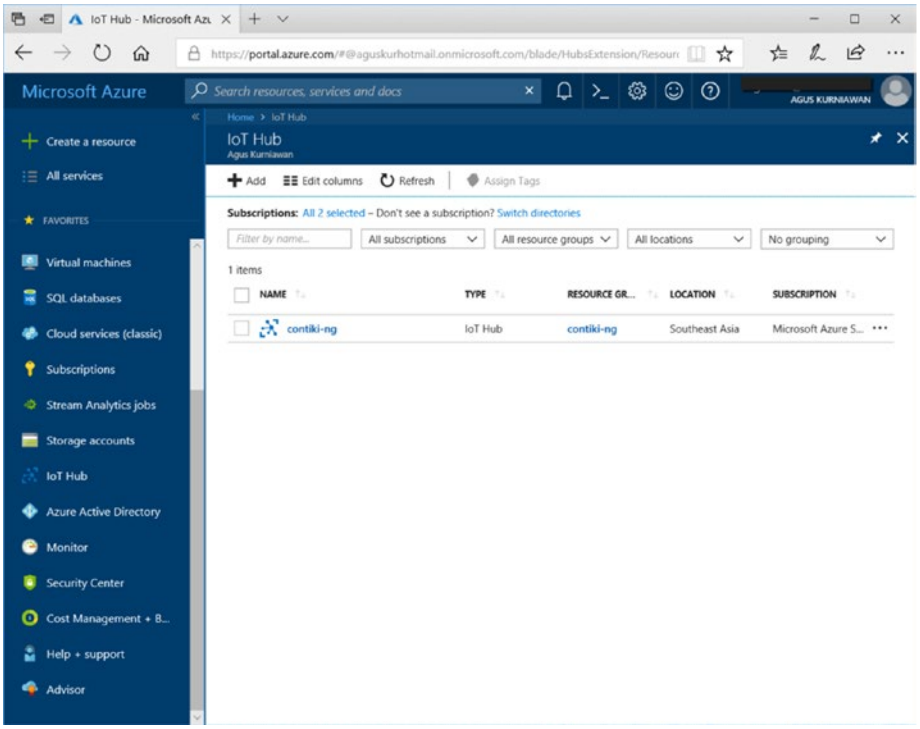


Figure 8-4. *Azure IoT Hub dashboard*

Fill in all required fields to create a new IoT Hub, which is included in your Azure subscription scheme. For instance, I created an Azure IoT Hub, called contiki-ng. After creating an Azure IoT Hub, you should see it on the Azure IoT Hub dashboard, which is shown in Figure 8-5.



NAME	TYPE	RESOURCE GR...	LOCATION	SUBSCRIPTION
contiki-ng	IoT Hub	contiki-ng	Southeast Asia	Microsoft Azure S...

Figure 8-5. *Created Azure IoT Hub for Contiki-NG*

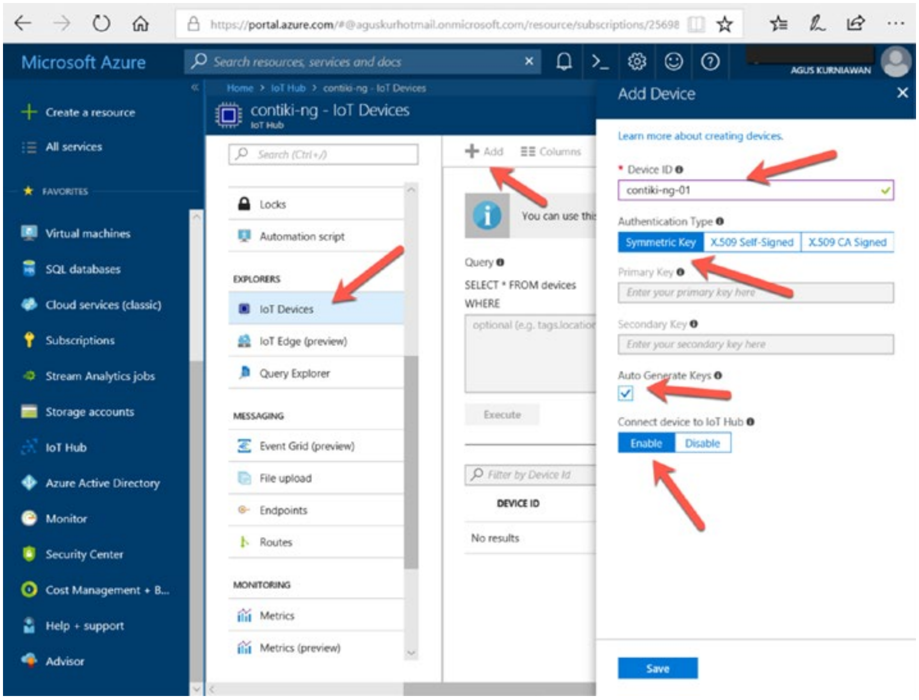
The next step is to register a new IoT device in order for it to access Azure IoT Hub. We will perform this task in the next section.

Registering a New IoT Device

Each IoT device that will access Azure IoT Hub should be registered in order to get an access key. Open your Azure IoT Hub and then click the "IoT Devices" menu so you see a list of IoT devices.

You can register a new IoT device by clicking the "+ Add" icon. You should get a registration form, shown in Figure 8-6.

Fill in your IoT device name. Select "Symmetric Key" for authentication type. You can check the box for "Auto Generate Keys" to generate keys automatically. Please select "Enable" for activating your IoT device. Click the Save button if you are done to add the IoT device.



Query
SELECT * FROM devices
WHERE
optional (e.g. tags.locatio

* Device ID: contiki-ng-01

Authentication Type: [✓ Symmetric Key] X.509 Self-Signed X.509 CA Signed

Primary Key: Enter your primary key here

Secondary Key: Enter your secondary key here

Auto Generate Keys: ✓

Connect device to IoT Hub: [✓ Enable] Disable

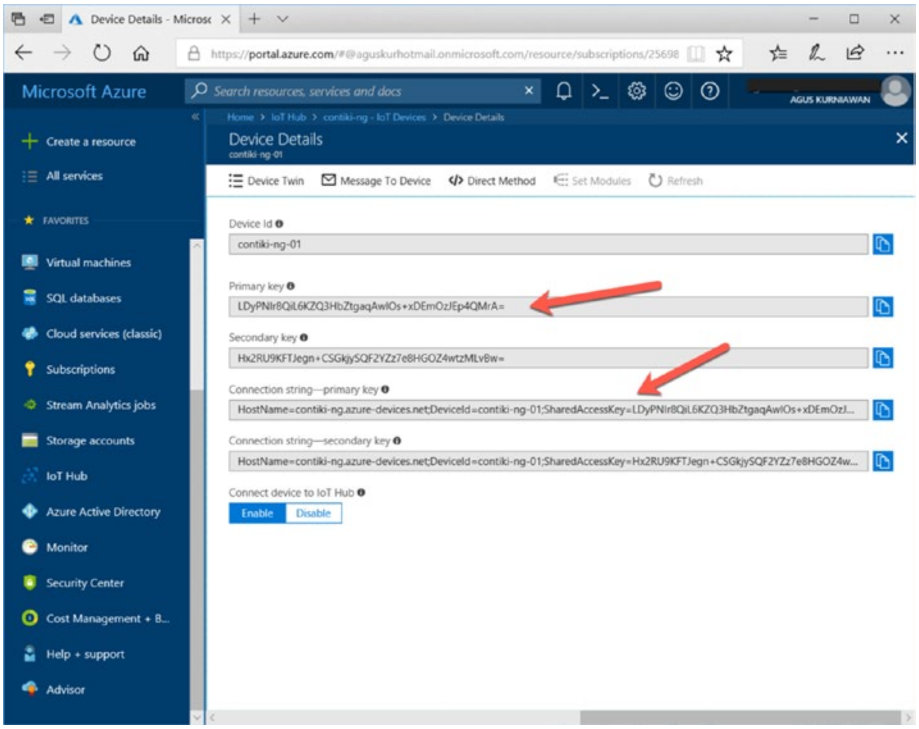
Figure 8-6. *Creating a new IoT device*

Copying Device Keys

After you have registered all IoT devices that will access Azure IoT Hub, you need to copy all IoT device keys. To obtain these keys, you can click your IoT devices on the Azure IoT Hub to get detailed information from the device.

You should see the IoT device key in the "Primary key" and "Connection string" fields. You can see it in Figure 8-7. You can copy the text that is indicated by an arrow. We will use these keys in our program.

Next, we will develop programs for Contiki-NG and a middleware application to communicate with the Azure IoT Hub. We will perform this task in the next section.



Device Id
contiki-ng-01

Primary key
LDyPNIr8QiL6KZQ3HbZtgaqAwIOs+xDEmOzJEp4QMrA=

Secondary key
Hx2RU9KFTJegn+CSGkjySQF2YZz7e8HGOZ4wtzMLvBw=

Connection string—primary key
HostName=contiki-ng.azure-devices.net;DeviceId=contiki-ng-01;SharedAccessKey=LDyPNIr8QiL6KZQ3HbZtgaqAwIOs+xDEmOzJ...

Connection string—secondary key
HostName=contiki-ng.azure-devices.net;DeviceId=contiki-ng-01;SharedAccessKey=Hx2RU9KFTJegn+CSGkjySQF2YZz7e8HGOZ4w...

Connect device to IoT Hub
[✓ Enable] Disable

Figure 8-7. *Copy the IoT device key and its connection string*

Developing Application

There are three applications that we are going to develop. First, we will develop two programs for Contiki-NG, starting with the 6LoWPAN router and sensor application. A 6LoWPAN router will be implemented by deploying an rpl-border-router program to the Contiki-NG mote. The sensor application runs a web server that waits for incoming requests from the sensor.

The second program that we will develop is a middleware application. This program will request sensor data from Contiki-NG. Then, this program will push it to the Azure IoT Hub.

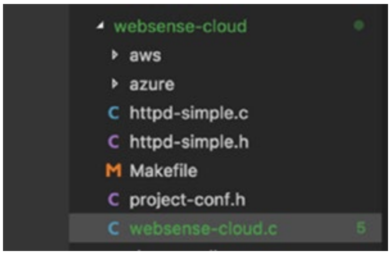
The last program is a sensor consumer program. The program will subscribe to the Azure IoT Hub to get sensor data from Contiki-NG. Once the middleware application pushes the sensor data to the Azure IoT Hub, the sensor consumer program will get the sensor data that is pushed by the Azure IoT Hub.

We will implement these programs in the next section.

Developing Programs for Contiki-NG

On the Contiki-NG side, we develop two programs for Contiki-NG, starting with the rpl-border-router and sensor program. You can find the rpl-border-router in the Contiki-NG program samples. You should compile and upload rpl-border-router to one of the Contiki-NG motes. You can read how to implement rpl-border-router in Chapter 6.

A sensor program is a web server that serves requests for sensor data. We use the websense program from Chapter 6. We set our project name as websense-Cloud. We rename `websense.c` as `websense-Cloud.c`. You can see the project structure of websense-Cloud in Figure 8-8.



```
websense-cloud
  aws
  azure
  httpd-simple.c
  httpd-simple.h
  Makefile
  project-conf.h
  websense-cloud.c
```

Figure 8-8. *Project structure for Contiki-NG and Azure*

In the `Makefile` file, you can configure the demo project to include `http-simple.c` and the Contiki-NG project. You can write these scripts:

```
CONTIKI_PROJECT = websense-Cloud
all: $(CONTIKI_PROJECT)

CONTIKI = ../..
PROJECT_SOURCEFILES += httpd-simple.c

include $(CONTIKI)/Makefile.include
```

We also modify the `websense-Cloud.c` file that is copied from the `websense.c` file (Chapter 6). In the `generate_routes()` method, we modify code in order to serve requests for sensor data. You can write this code:

```
static
PT_THREAD(generate_routes(struct httpd_state *s))
{
  char buff[35];

  PSOCK_BEGIN(&s->sout);
  //SEND_STRING(&s->sout, TOP);

  int temperature = 15 + rand() % 25;
  int humidity = 80 + rand() % 10;

  sprintf(buff,"{\"temp\":%u,\"hum\":%u}", temperature, humidity);
  printf("send json to requester\n");

  SEND_STRING(&s->sout, buff);
  //SEND_STRING(&s->sout, BOTTOM);

  PSOCK_END(&s->sout);
}
```

Save all changes. Compile the rpl-border-router and websense-Cloud programs. Then, upload those to your Contiki-NG motes.

Next, we will develop the middleware application using Node.js.

Building Azure Middleware Application

We will develop an Azure middleware application to request sensor data from Contiki-NG and push sensor data to Azure IoT Hub. For implementation, we use Node.js.

First, create a folder for your project. Open Terminal and navigate to your project folder. Then, initialize your project, including required libraries. Type these commands:

```
$ npm init
$ npm install azure-iot-device azure-iot-device-mqtt express
--save
```

Now, we will start to write a middleware application for Azure. Create a file, called `middleware-azure.js`. Initialize all required libraries and run the web server on port 3000. You also need information such as hostname, device ID, and shared access key. Write this code:

```
'use strict';

var express = require('express');
var request = require('request');
var app = express();
var http = require('http').Server(app);

var clientFromConnectionString = require('azure-iot-device-
mqtt').clientFromConnectionString;
var Message = require('azure-iot-device').Message;

var connectionString = 'HostName={youriothostname};DeviceId=myF
irstNodeDevice;SharedAccessKey={yourdevicekey}';
var mydeviceId = 'contiki-ng-01';
var client = clientFromConnectionString(connectionString);

app.get('/', function(req, res){
    res.send('WebSense Azure Cloud');
});

http.listen(3000, function(){
    console.log('listening on *:3000');
    console.log('websense azure Cloud was started');
});
```

You should change value connectionString to the following values:

- {youriothostname} is your domain address (IP address) from your Azure IoT Hub
- myFirstNodeDevice and mydeviceId are your registered device ID
- {yourdevicekey} is a shared access key. You can find it in the primary key field from your registered IoT device; see Figure 8-7.

Next, we declare two functions. One of these functions, printResultFor(), is used to print all messages to Terminal. The other is the callback function, connectCallback, which requests sensor data from Contiki-NG motes:

```
function printResultFor(op) {
    return function printResult(err, res) {
      if (err) console.log(op + ' error: ' + err.toString());
      if (res) console.log(op + ' status: ' + res.constructor.
      name);
    };
  }

var connectCallback = function (err) {
    if (err) {
        console.log('Could not connect: ' + err);
    } else {
        console.log('Client connected');

        // Create a message and send it to the IoT Hub every
        second
        setInterval(function(){

            request.get('http://[fd00::212:4b00:797:6083]/',
            function(err,res,body){
                if(err){
                    console.log(err);
                    return;
                }
                var obj = JSON.parse(body);
                console.log(obj);

                var temperature = obj.temp;
                var humidity = obj.hum;
                var data = JSON.stringify({ deviceId:
                mydeviceId, temperature: temperature, humidity:
                humidity });
                var message = new Message(data);
                message.properties.add('temperatureAlert',
                (temperature > 30) ? 'true' : 'false');
                console.log("Sending message: " + message.
                getData());
                client.sendEvent(message,
                printResultFor('send'));

            });
        }, 3000);
    }
};
```

You should replace the value `[fd00::212:4b00:797:6083]` with the IPv6 address from the Contiki-NG mote that runs the websense-Cloud application.

Finally, we call our callback function from the Azure object:

```
client.open(connectCallback);
console.log('Contiki-NG Azure Middleware started.');
```

Save all these codes.

Developing Sensor Consumer Program

The last step is to develop a sensor consumer program to subscribe to Azure IoT Hub in order to retrieve sensor data.

We use the same project from the previous section. We need the `azure-vent-hubs` library to create the subscription. Type this command:

```
$ npm install azure-event-hubs --save
```

Then, we create a file, called `azure-sensor-subscriber.js`. We initialize a required library and configure a connection string for the Azure IoT Hub. Write this code:

```
'use strict';


var EventHubClient = require('azure-event-hubs').Client;
var connectionString = 'HostName={youriothostname};DeviceId=
                        myFirstNodeDevice;SharedAccessKey=
                        {yourdevicekey}';

var printError = function (err) {
    console.log(err.message);
};

var printMessage = function (message) {
    console.log('Message received: ');
    console.log(JSON.stringify(message.body));
    console.log('');
};
```

Change `connectionString` to the previous value.

Now, we subscribe and listen to incoming messages from Azure IoT Hub. Write this code:

```
var client = EventHubClient.fromConnectionString(connectionString);
client.open()
    .then(client.getPartitionIds.bind(client))
    .then(function (partitionIds) {
        return partitionIds.map(function (partitionId) {
            return client.createReceiver('$Default',
            partitionId, { 'startAfterTime' : Date.now()}).
            then(function(receiver) {
                console.log('Created partition receiver: ' +
                partitionId)
                receiver.on('errorReceived', printError);
                receiver.on('message', printMessage);
            });
        });
    })
.catch(printError);
```

Save all files.

We have written all programs for this demo. Next, we will test our project.

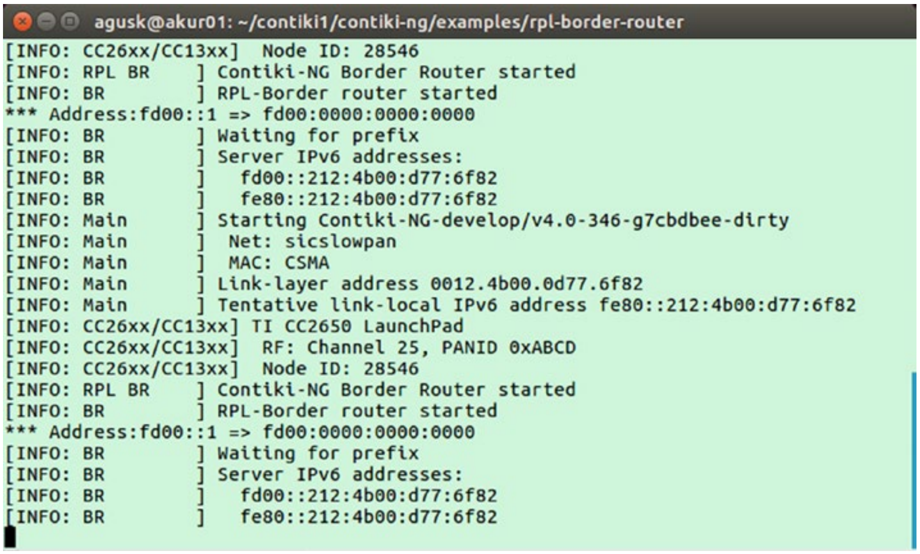
Testing Contiki-NG and Azure Application

In this section, I will assume you have already deployed all programs into your Contiki-NG motes. First, run the rpl-border-router program on the 6LoWPAN router. For instance, I run it on a TI LaunchPad CC2650. Then, navigate to the `rpl-border-router` project folder. Then, run this:

```
$ make TARGET=srf06-cc26xx BOARD=launchpad/cc2650 connect-router
```

After execution, that command will run tunslip6. Change TARGET to your Contiki-NG platform. If it succeeds, you can turn on another Contiki-NG mote that has installed the sensor application.

Try to perform ping6 to check that your Contiki-NG mote can be reached from a computer. You can see the program output from the rpl-border-router application in Figure 8-9.



```
agusk@akur01: ~/contiki1/contiki-ng/examples/rpl-border-router
[INFO: CC26xx/CC13xx]  Node ID: 28546
[INFO: RPL BR    ] Contiki-NG Border Router started
[INFO: BR        ] RPL-Border router started
*** Address:fd00::1 => fd00:0000:0000:0000
[INFO: BR        ] Waiting for prefix
[INFO: BR        ] Server IPv6 addresses:
[INFO: BR        ]   fd00::212:4b00:d77:6f82
[INFO: BR        ]   fe80::212:4b00:d77:6f82
[INFO: Main      ] Starting Contiki-NG-develop/v4.0-346-g7cbdbee-dirty
[INFO: Main      ]  Net: sicslowpan
[INFO: Main      ]  MAC: CSMA
[INFO: Main      ] Link-layer address 0012.4b00.0d77.6f82
[INFO: Main      ] Tentative link-local IPv6 address fe80::212:4b00:d77:6f82
[INFO: CC26xx/CC13xx] TI CC2650 LaunchPad
[INFO: CC26xx/CC13xx]  RF: Channel 25, PANID 0xABCD
[INFO: CC26xx/CC13xx]  Node ID: 28546
[INFO: RPL BR    ] Contiki-NG Border Router started
[INFO: BR        ] RPL-Border router started
*** Address:fd00::1 => fd00:0000:0000:0000
[INFO: BR        ] Waiting for prefix
[INFO: BR        ] Server IPv6 addresses:
[INFO: BR        ]   fd00::212:4b00:d77:6f82
[INFO: BR        ]   fe80::212:4b00:d77:6f82
```

Figure 8-9. *Running 6LoWPAN router application*

Now, you can run the middleware application in Terminal. You can type this command:

```
$ node middleware-azure.js
```

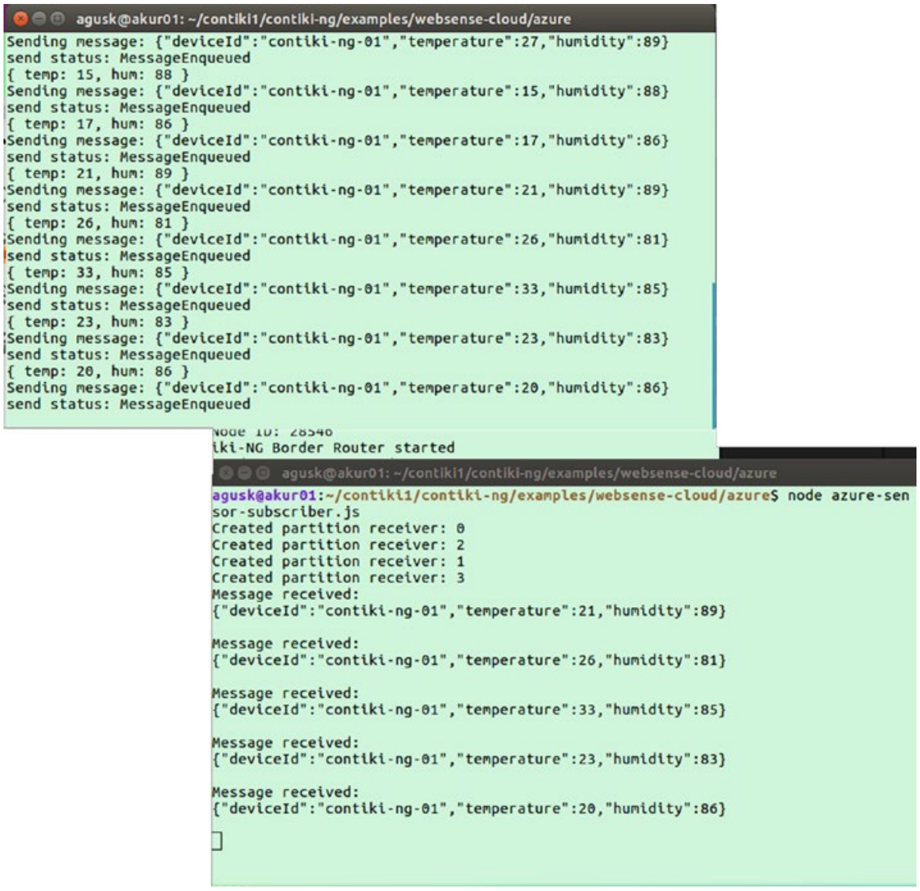
Then, you can run the sensor application to listen for incoming sensor data from Azure IoT Hub. Open a new Terminal and then type this command:

```
$ node azure-sensor-subscriber.js
```

The middleware application will request sensor data from the Contiki-NG mote every three seconds. After obtaining sensor data, the middleware application will push the data to the Azure IoT Hub.

Once sensor data has reached the Azure IoT Hub, it will be distributed to all subscribers.

You can see a sample of the program output of the middleware application and the sensor application in Figure 8-10.



agusk@akur01: ~/contiki1/contiki-ng/examples/websense-cloud/azure

```
Sending message: {"deviceId":"contiki-ng-01","temperature":27,"humidity":89}
send status: MessageEnqueued
{ temp: 15, hum: 88 }
Sending message: {"deviceId":"contiki-ng-01","temperature":15,"humidity":88}
send status: MessageEnqueued
{ temp: 17, hum: 86 }
Sending message: {"deviceId":"contiki-ng-01","temperature":17,"humidity":86}
send status: MessageEnqueued
{ temp: 21, hum: 89 }
Sending message: {"deviceId":"contiki-ng-01","temperature":21,"humidity":89}
send status: MessageEnqueued
{ temp: 26, hum: 81 }
Sending message: {"deviceId":"contiki-ng-01","temperature":26,"humidity":81}
send status: MessageEnqueued
{ temp: 33, hum: 85 }
Sending message: {"deviceId":"contiki-ng-01","temperature":33,"humidity":85}
send status: MessageEnqueued
{ temp: 23, hum: 83 }
Sending message: {"deviceId":"contiki-ng-01","temperature":23,"humidity":83}
send status: MessageEnqueued
{ temp: 20, hum: 86 }
Sending message: {"deviceId":"contiki-ng-01","temperature":20,"humidity":86}
send status: MessageEnqueued
```

```
Node ID: 28546
iki-NG Border Router started
```

agusk@akur01: ~/contiki1/contiki-ng/examples/websense-cloud/azure

```
agusk@akur01:~/contiki1/contiki-ng/examples/websense-cloud/azure$ node azure-sen
sor-subscriber.js
Created partition receiver: 0
Created partition receiver: 2
Created partition receiver: 1
Created partition receiver: 3
Message received:
{"deviceId":"contiki-ng-01","temperature":21,"humidity":89}

Message received:
{"deviceId":"contiki-ng-01","temperature":26,"humidity":81}

Message received:
{"deviceId":"contiki-ng-01","temperature":33,"humidity":85}

Message received:
{"deviceId":"contiki-ng-01","temperature":23,"humidity":83}

Message received:
{"deviceId":"contiki-ng-01","temperature":20,"humidity":86}
```

Figure 8-10. *Running middleware application and sensor program*

Demo 2: Contiki-NG and Amazon AWS

In this demo, we will perform the same scenario as in the first demo. We will use Amazon AWS. To communicate with IoT devices, Amazon AWS provides a service called AWS IoT. You can read about it at `https://aws.amazon.com/iot/`.

Our demo scenario can be seen in Figure 8-11. This is similar to the first demo. A middleware application will get sensor data from Contiki-NG and then push it to Amazon AWS IoT.

Next, we will implement our demo by performing some tasks, as follows:

- Prepare to set up AWS IoT.
- Develop applications for Contiki-NG and middleware.
- Test all programs.

Each task will be implemented in the next section.

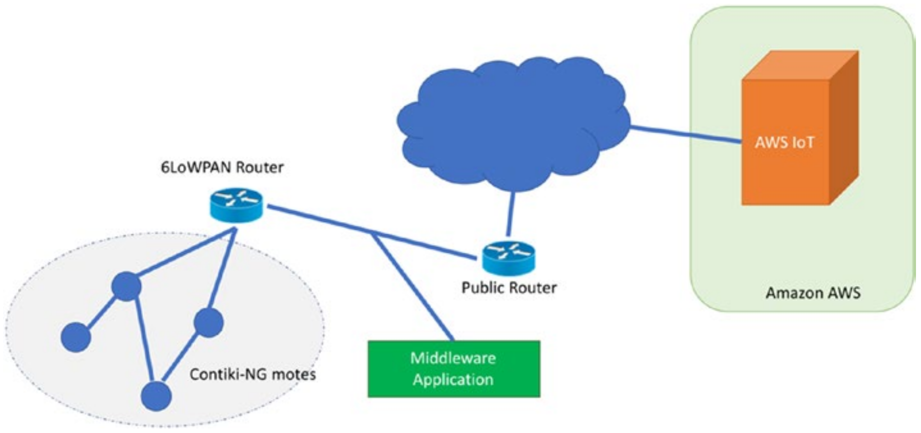


***Figure 8-11.** Demo project scenario for Contiki-NG and Amazon AWS IoT*

Preparation

In this section, we will set up AWS IoT to create a thing. Then, we will configure security tasks, such as creating a certificate and its keys. To set up AWS IoT for our demo, we will perform the following tasks:

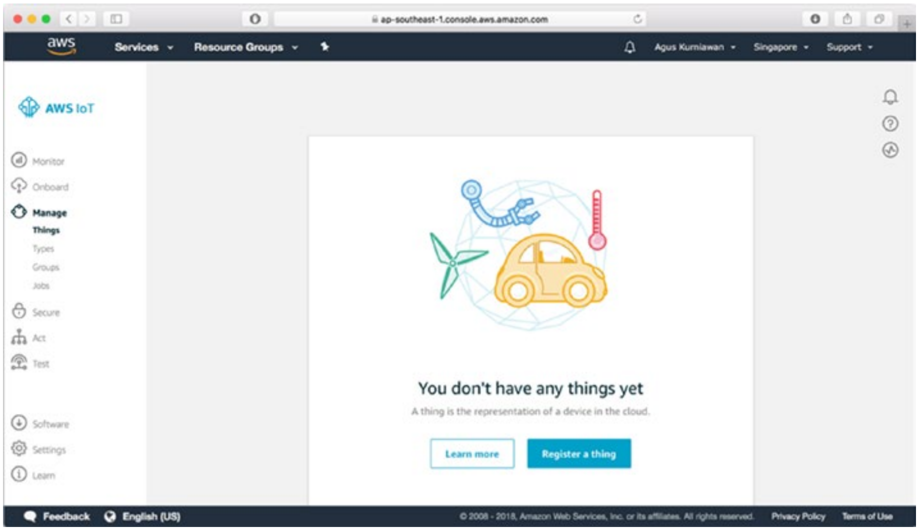
- Create a new IoT thing.
- Create a policy for AWS IoT.
- Attach a policy and a thing to a certificate.

These tasks will be explained in the next section.

Creating a New IoT Thing

Each IoT device that wants to access AWS IoT should be registered so as to obtain the access keys included with the security certificate.

First, open a browser and navigate to `https://aws.amazon.com/iot/`, so you should see the AWS IoT dashboard shown in Figure 8-12.



You don't have any things yet

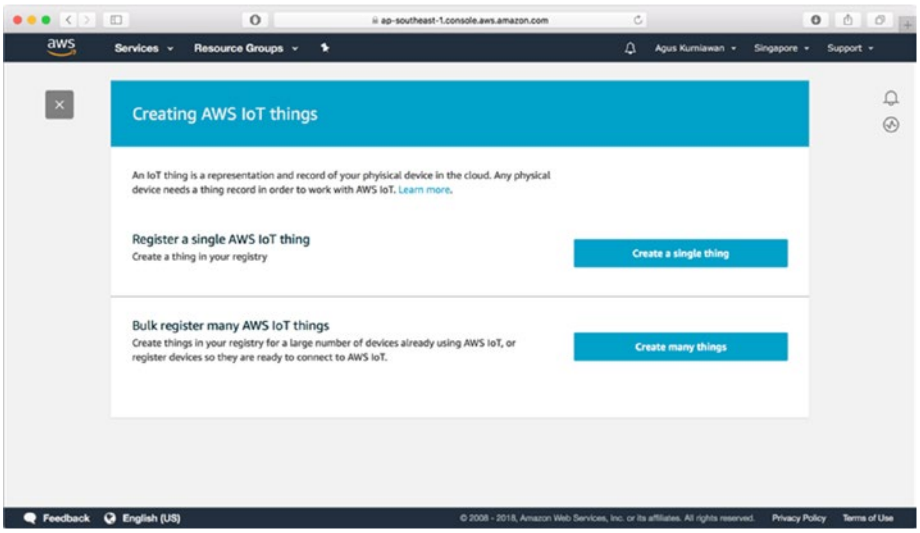
A thing is the representation of a device in the cloud.

© 2008 - 2018, Amazon Web Services, Inc. or its affiliates. All rights reserved.

Figure 8-12. AWS IoT console management

On the left-hand menu, click "Manage Things." If you don't create things yet, you can click "Register a thing" to register a new IoT device.

After clicking, you should get a form like that shown in Figure 8-13. To simply begin a registration process, click "Create a single thing."


ap-southeast-1.console.aws.amazon.com
aws
Services
Resource Groups
Agus Kurniawan
Singapore
Support
Feedback
English (US)
© 2008 - 2018, Amazon Web Services, Inc. or its affiliates. All rights reserved.
Privacy Policy
Terms of Use

Creating AWS IoT things

An IoT thing is a representation and record of your physical device in the cloud. Any physical device needs a thing record in order to work with AWS IoT. Learn more.

Register a single AWS IoT thing
Create a thing in your registry

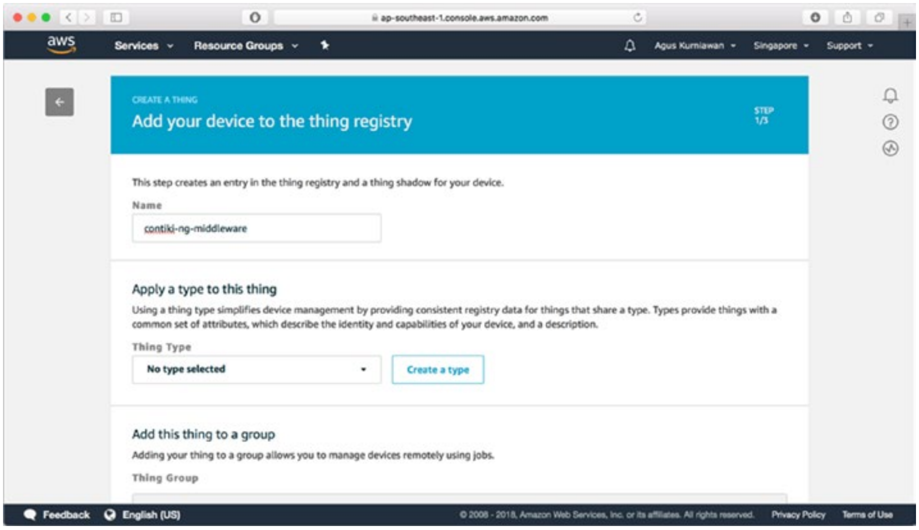
Create a single thing

Bulk register many AWS IoT things
Create things in your registry for a large number of devices already using AWS IoT, or register devices so they are ready to connect to AWS IoT.

Create many things

Figure 8-13. *Creating AWS IoT things*

You should fill in the IoT device information. A thing name is required. For instance, I called my thing contiki-ng-middleware. You can see it in Figure 8-14.



Add your device to the thing registry

This step creates an entry in the thing registry and a thing shadow for your device.

Name: contiki-ng-middleware

Apply a type to this thing

Using a thing type simplifies device management by providing consistent registry data for things that share a type. Types provide things with a common set of attributes, which describe the identity and capabilities of your device, and a description.

Thing Type: No type selected | Create a type

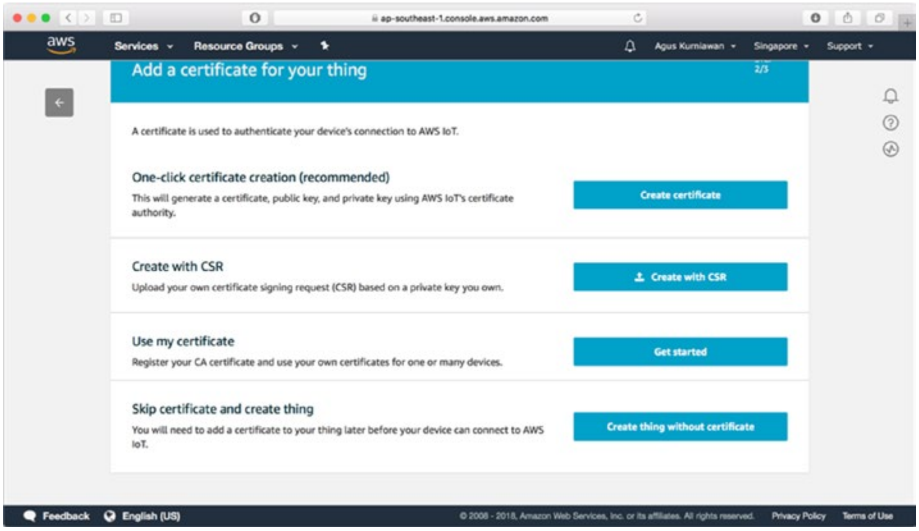
Add this thing to a group

Adding your thing to a group allows you to manage devices remotely using jobs.

Thing Group

Figure 8-14. *Setting an IoT device*

If you have finished creating a thing, you should get the form that is shown in Figure 8-15. To access AWS IoT, we need a certificate. In this demo, we create a new certificate. You can use your own certificate. Click "Create certification."


ap-southeast-1.console.aws.amazon.com
aws
Services
Resource Groups
Agus Kurniawan
Singapore
Support
2/3
Create certificate
Create with CSR
Get started
Create thing without certificate
Feedback
English (US)
© 2008 - 2018, Amazon Web Services, Inc. or its affiliates. All rights reserved.
Privacy Policy
Terms of Use

Add a certificate for your thing

A certificate is used to authenticate your device's connection to AWS IoT.

One-click certificate creation (recommended)

This will generate a certificate, public key, and private key using AWS IoT's certificate authority.

Create with CSR

Upload your own certificate signing request (CSR) based on a private key you own.

Use my certificate

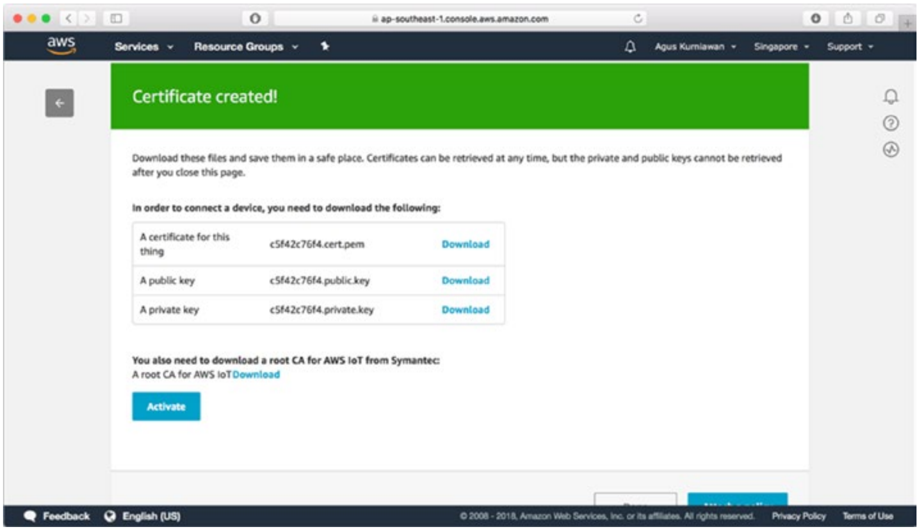
Register your CA certificate and use your own certificates for one or many devices.

Skip certificate and create thing

You will need to add a certificate to your thing later before your device can connect to AWS IoT.

Figure 8-15. *Adding a certificate*

After clicking that button, you should see the form that is shown in Figure 8-16. To activate your certificate, click the "Activate" button.


ap-southeast-1.console.aws.amazon.com
aws
Services
Resource Groups
Agus Kurniawan
Singapore
Support
Activate
Feedback
English (US)
© 2008 - 2018, Amazon Web Services, Inc. or its affiliates. All rights reserved.
Privacy Policy
Terms of Use

Certificate created!

Download these files and save them in a safe place. Certificates can be retrieved at any time, but the private and public keys cannot be retrieved after you close this page.

In order to connect a device, you need to download the following:

A certificate for this thing	c5f42c76f4.cert.pem	Download
A public key	c5f42c76f4.public.key	Download
A private key	c5f42c76f4.private.key	Download

You also need to download a root CA for AWS IoT from Symantec:
A root CA for AWS IoT Download

Figure 8-16. *Generating certificate and keys*

Download all files for the certificate and public/private keys. You also need to download a root CA (Certificate Authority) for AWS IoT from the link shown in Figure 8-16. Put them in a folder; for instance, `certs`. You can see my certificate and key files in Figure 8-17.

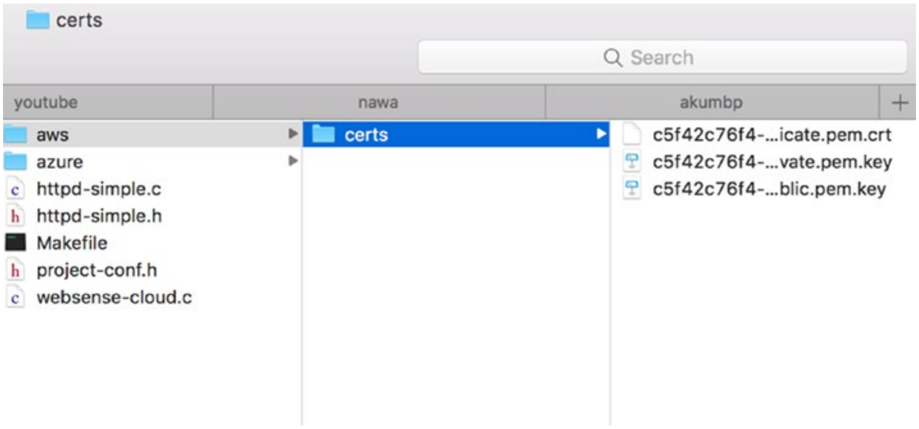


Figure 8-17. *Download certificate and key files*

Now, you should see the created thing in the Manage Things dashboard, shown in Figure 8-18. You can create more than two things for AWS IoT.

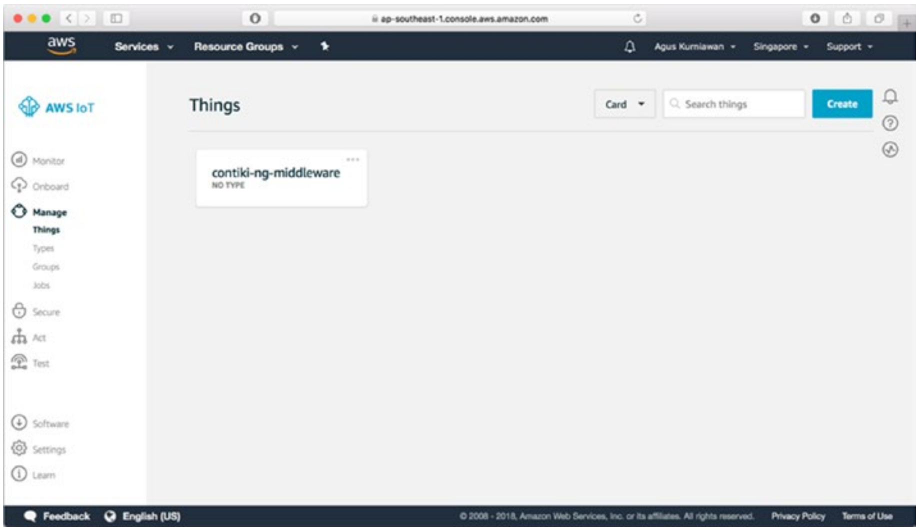
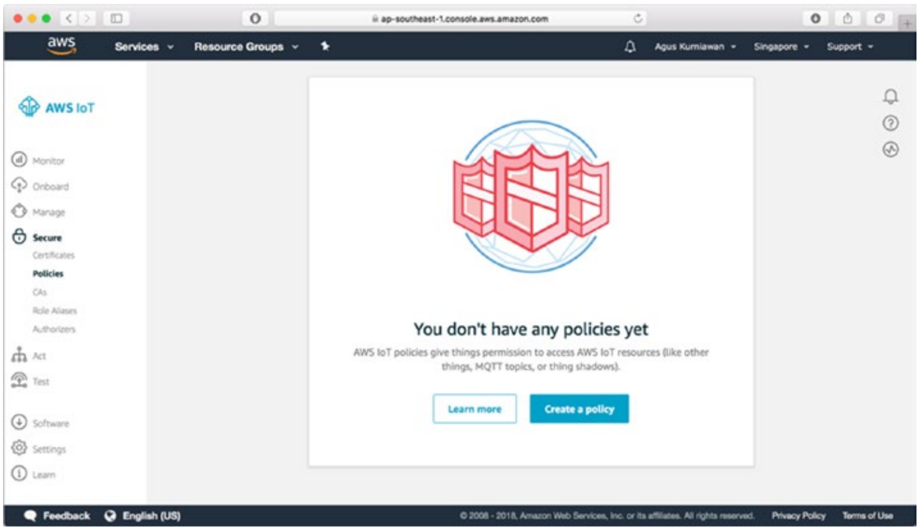


Figure 8-18. *A new thing shown on Manage Things dashboard*

Next, we will create a policy to enable our thing to access the AWS IoT Hub.

Creating a Policy for AWS IoT

In this section, we will create a policy for AWS IoT. We need this policy to manage all device access. You can find a policy dashboard by clicking "Secure," then "Policies." You can see it in Figure 8-19.



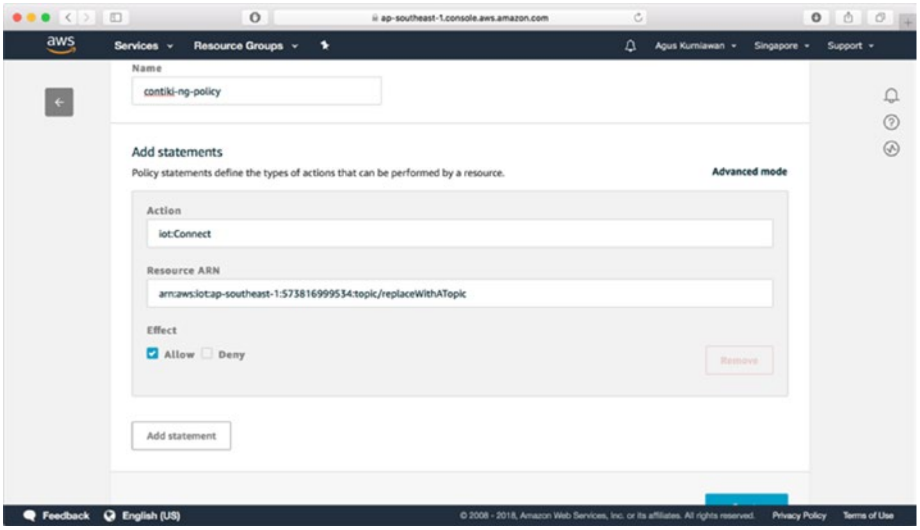
You don't have any policies yet

AWS IoT policies give things permission to access AWS IoT resources (like other things, MQTT topics, or thing shadows).

Figure 8-19. *AWS IoT policy dashboard*

Click "Create a policy." Then, you should see the form shown in Figure 8-20. Fill in the policy name. Next, you should add statements to work with AWS IoT. You should add resource, action, and effect for four items, as follows:

```
{
  "Version": "2012-10-17",
  "Statement": [
    {
      "Effect": "Allow",
      "Action": "iot:Connect",
      "Resource": "*"
    },
    {
      "Effect": "Allow",
      "Action": "iot:Publish",
      "Resource": "*"
    },
    {
      "Effect": "Allow",
      "Action": "iot:Subscribe",
      "Resource": "*"
    },
    {
      "Effect": "Allow",
      "Action": "iot:Receive",
      "Resource": "*"
    }
  ]
}
```


Name: contiki-ng-policy

Add statements

Policy statements define the types of actions that can be performed by a resource.

Action: iot:Connect

Resource ARN: arn:aws:iot:ap-southeast-1:573816999534:topic/replaceWithATopic

Effect: [✓ Allow] Deny

Figure 8-20. *Adding a new policy for AWS IoT*

After creating a policy, you can verify your policy in Secure ➤ Policies from the AWS IoT dashboard. You can see it in Figure 8-21.

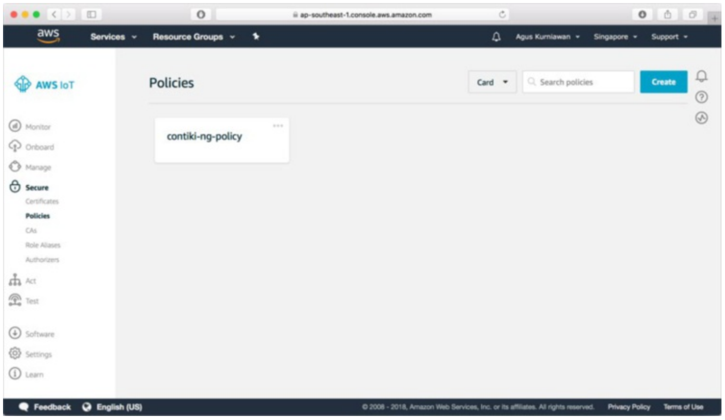


Figure 8-21. *A created policy shows up in Policies dashboard.*

Next, we map a policy and a thing to a certificate. We will perform this in the next section.

Attaching a Policy and a Thing to a Certificate

Your policy and thing should be mapped to a certificate that is already activated in AWS IoT. To perform this task, you can visit Secure ➤ Certificates. You should see your certificate. Click the ... icon so you see the context menu shown in Figure 8-22.

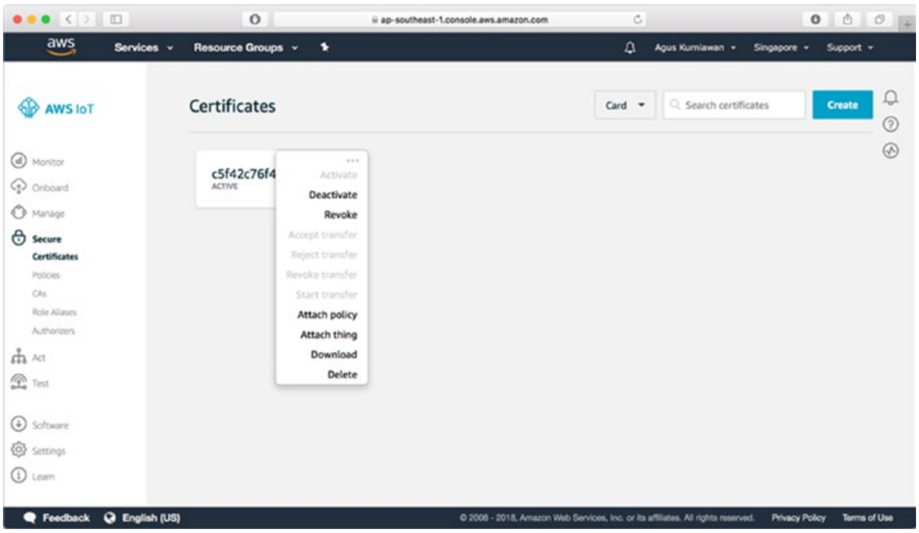
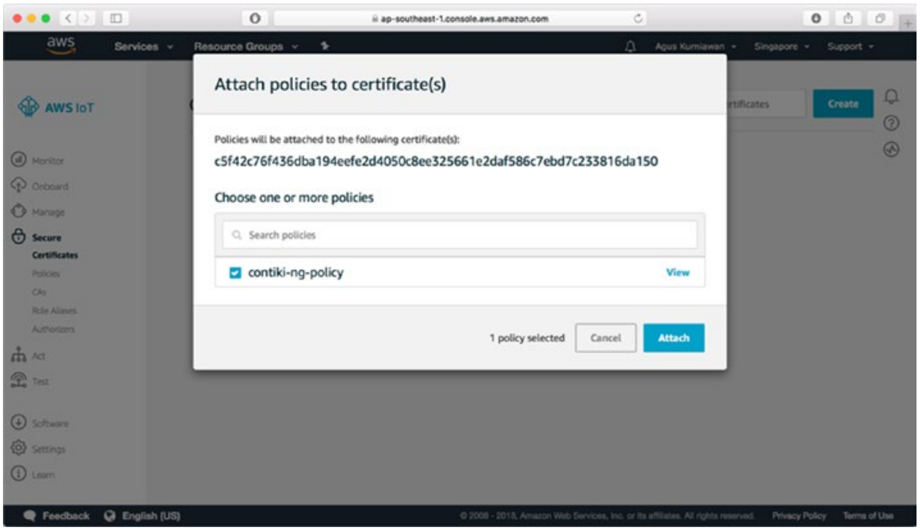


Figure 8-22. *Open context menu of a certificate of AWS IoT*

Click menu Attach policy so you see the form dialog that is shown in Figure 8-23. Select your policy that has already been created. If done, click the Attach button.


Attach policies to certificate(s)

Policies will be attached to the following certificate(s):
c5f42c76f436dba194eefe2d4050c8ee325661e2daf586c7ebd7c233816da150

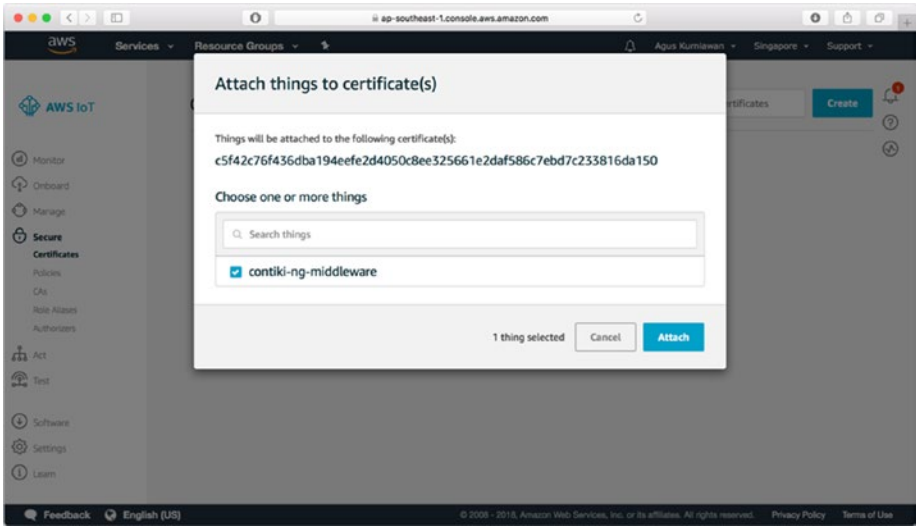
Choose one or more policies

☑ contiki-ng-policy

1 policy selected

Figure 8-23. *Attach a policy to a certificate*

Next, we should attach the thing to a certificate. From Figure 8-22, select menu "Attach thing" so you get the form dialog shown in Figure 8-24.


Attach things to certificate(s)

Things will be attached to the following certificate(s):
c5f42c76f436dba194eefe2d4050c8ee325661e2daf586c7ebd7c233816da150

Choose one or more things

☑ contiki-ng-middleware

1 thing selected

Figure 8-24. *Add an IoT device (thing) to a certificate*

Select your thing that was already created.

Finally, you have to set up AWS IoT. Next, we will develop programs for Contiki-NG and the middleware application.

Developing Application

In this section, we will develop applications for Contiki-NG and Node.js to access AWS IoT.

Developing Programs for Contiki-NG

Since our demo scenario is similar to the previous demo, we use the same configuration. You need one Contiki-NG mote as the 6LoWPAN router. Other Contiki-NG motes run the sensor application.

Please read the first demo to build programs for Contiki-NG.

Building Middleware Application for AWS IoT

We build an AWS middleware application to request sensor data from Contiki-NG and push sensor data to AWS IoT. For implementation, we use Node.js.

To create a project, you can create a folder. Then, open Terminal and navigate to your project folder. Then, initialize your project, including the required libraries. Type these commands:

```
$ npm init
$ npm install aws-iot-device-sdk request express --save
```

Now, we start to write a middleware application for AWS. Create a file, called `middleware-aws.js`. We now call the required libraries and configure AWS IoT. You can write this code:

```
var awsIot = require('aws-iot-device-sdk');
var express = require('express');
var request = require('request');
var app = express();
var http = require('http').Server(app);

var device = awsIot.device({
  keyPath: 'certs/private.pem.key',
  certPath: 'certs/certificate.pem.crt',
    caPath: 'certs/root-CA.pem',
      host: '<hostname>.iot.<region>.amazonaws.com',
  clientId: 'contiki-ng',
    region: '<region>'
 });
```

You should change the values for `keyPath`, `certPath`, `caPath`, and `region` to those for AWS IoT.

We also run a web server using Express on port 3000:

```
app.get('/', function(req, res){
    res.send('WebSense Azure Cloud');
});

http.listen(3000, function(){
    console.log('listening on *:3000');
    console.log('websense aws Cloud was started');
});
```

Next, we listen for the connect event from AWS IoT. Once the middleware application is connected to AWS IoT, we request sensor data from Contiki-NG every three seconds. For testing, I request data from Contiki-NG with the IPv6 address `[fd00::212:4b00:797:6083]`. You can change it. You also can change `mydeviceId`:

```
var isSubscribe = true;
device
.on('connect', function() {
  console.log('connected to AWS IoT.');
  // optional to subscribe
  if(isSubscribe)
    device.subscribe('contiki-ng-sensor');

  setInterval(function(){


    request.get('http://[fd00::212:4b00:797:6083]/',function
    (err,res,body){
        if(err){
            console.log(err);
            return;
        }
        var obj = JSON.parse(body);
        console.log(obj);

        var temperature = obj.temp;
        var humidity = obj.hum;
        mydeviceId = 'fd00::212:4b00:797:6083';
        var data = JSON.stringify({ deviceId: mydeviceId,
        temperature: temperature, humidity: humidity });
        device.publish('contiki-ng-sensor', data);
        console.log('sent: ', JSON.stringify(data));

    });
  }, 3000);
});
```

Last, we can subscribe to the `contiki-ng-sensor` channel:

```
// optional to subscribe
device
   .on('message', function(topic, payload) {
     console.log('recv: ', topic, payload.toString());
});

console.log('Contiki-NG AWS Middleware started.');
```

Save all code.

Next, we will test this project.

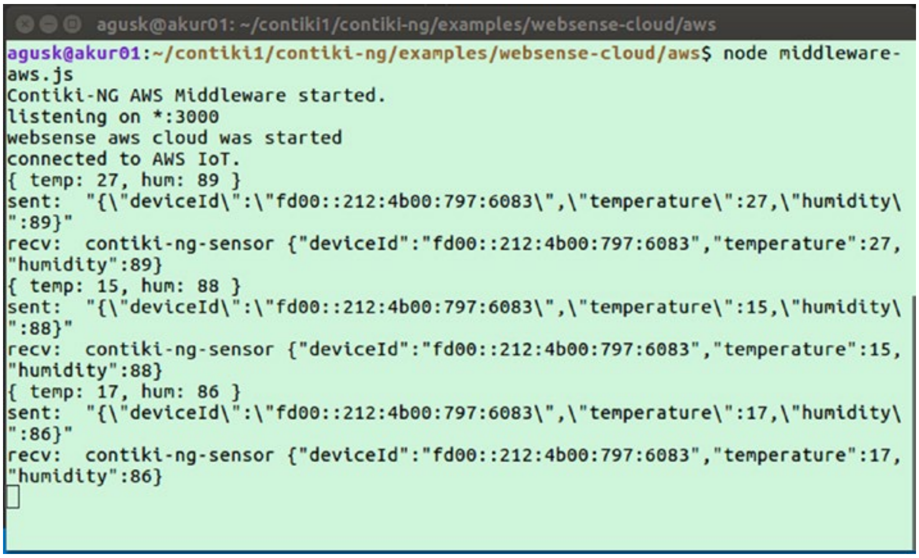
Testing Contiki-NG and AWS IoT

Deploy all programs to Contiki-NG. Then, run the 6LoWPAN router and the middleware application:

```
$ node middleware-aws.js
```

This program will connect to AWS IoT. After connecting, this application will retrieve sensor data from Contiki-NG. It will then push the sensor data to AWS IoT.

Since the middleware application subscribes to AWS IoT, this program will receive incoming data from AWS IoT. You can see my program output in Figure 8-25.

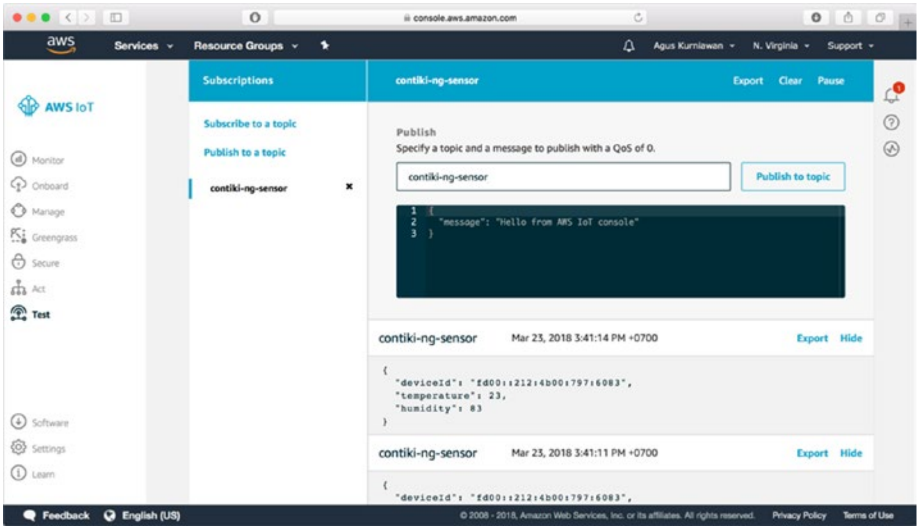

agusk@akur01: ~/contiki1/contiki-ng/examples/websense-cloud/aws

```
agusk@akur01:~/contiki1/contiki-ng/examples/websense-cloud/aws$ node middleware-
aws.js
Contiki-NG AWS Middleware started.
listening on *:3000
websense aws cloud was started
connected to AWS IoT.
{ temp: 27, hum: 89 }
sent:  "{\"deviceId\":\"fd00::212:4b00:797:6083\",\"temperature\":27,\"humidity\
":89}"
recv:  contiki-ng-sensor {"deviceId":"fd00::212:4b00:797:6083","temperature":27,
"humidity":89}
{ temp: 15, hum: 88 }
sent:  "{\"deviceId\":\"fd00::212:4b00:797:6083\",\"temperature\":15,\"humidity\
":88}"
recv:  contiki-ng-sensor {"deviceId":"fd00::212:4b00:797:6083","temperature":15,
"humidity":88}
{ temp: 17, hum: 86 }
sent:  "{\"deviceId\":\"fd00::212:4b00:797:6083\",\"temperature\":17,\"humidity\
":86}"
recv:  contiki-ng-sensor {"deviceId":"fd00::212:4b00:797:6083","temperature":17,
"humidity":86}
```

Figure 8-25. *Program output from executing middleware application*

For a subscriber tool, you can use the Subscription test application. You can find it on the Test menu.

After clicking it, you will see the form shown in Figure 8-26. Select "Subscribe to a topic." Then, fill in "contiki-ng-sensor" for listening incoming messages.



Publish
Specify a topic and a message to publish with a QoS of 0.

contiki-ng-sensor

```
{
  "message": "Hello from AWS IoT console"
}
```

contiki-ng-sensor Mar 23, 2018 3:41:14 PM +0700

```
{
  "deviceId": "fd00::212:4b00:797:6083",
  "temperature": 23,
  "humidity": 83
}
```

contiki-ng-sensor Mar 23, 2018 3:41:11 PM +0700

```
{
  "deviceId": "fd00::212:4b00:797:6083",
```

Figure 8-26. *Listening for incoming messages from AWS IoT Test*

You have finished integrating between Contiki-NG and the Cloud server. You practice more to hone your skills.

Summary

We have learned what Cloud computing is. We also developed programs to allow interaction between Contiki-NG motes and Cloud servers. We tested these programs using Microsoft Azure and Amazon AWS. Next, you could explore various features in Azure and AWS. You can use other Cloud platforms to integrate with Contiki-NG.

Index