IOT EMULATION WITH COOJA

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ICTP-IoT Workshop, Trieste 16-27 March 2015

Outline

- What is Cooja
  - Emulator vs Simulator
  - Main steps
  - Hello-world
- More examples
  - UDP-RPL/broadcast
  - Z1 sensors
  - Sense/Send/Blink
  - UDP-RPL/Unicast
- Energy monitoring
  - Timeline
  - Energest
  - Powertrace
  - PowerTracker
- Networking protocols
  - RPL
  - LIBP
  - Multi-sink

Cooja is an emulator

- According to different sources, an emulator is:
  - a hardware or software system that enables one computer system (called the *host*) to *behave like another* computer system (called the *guest*): e.g. Cooja enabling your laptop to behave like a Z1 mote.
  - a system that typically *enables* the host system *to run software or use peripheral devices* designed for the guest system: e.g. Cooja enabling your laptop to run the RPL protocol, LIBP and/or other IoT protocols of interest .

Cooja is an emulator

- According to different sources, an emulator is:
  - a system that *behaves exactly like* the guest system, and abides by all of the rules of the system being emulated, but operating in a different environment to the environment of the original emulated system.
  - a *complete replication* of the guest system, right down to being binary compatible with the emulated system's inputs and outputs.

Cooja is not a simulator

- According to different sources, a simulator is:
  - hardware or software that *enables* one computer system (called the *host*) *to behave like another* computer system (called the *guest*), *but* is implemented in an entirely *different way* : e.g. A flight simulator gives you the feeling of flying an airplane, but you are completely disconnected from the reality of flying the plane, and you can bend or break those rules as you see fit. e.g. Fly an Airbus A380 upside down between London and Sydney without breaking it.

Cooja is not a simulator

- According to different sources, a simulator is:
  - a system that *provides the basic behaviour* of a system *but may not* necessarily *abide by all of the rules* of the system being simulated.
  - a system designed to *recreate the operation or behaviour* of the guest system. The underlying principles can be the same as the original or different.

What is Cooja?

- Cooja is a Contiki network emulator
  - An extensible Java-based simulator capable of emulating Tmote Sky (and other) nodes
- The code to be executed by the node is the exact same firmware you may upload to physical nodes
- Allows large and small networks of motes to be simulated
- Motes can be emulated at the hardware level
  - Slower but allows for precise inspection of system behaviour
- Motes can also be emulated at a less detailed level
  - Faster and allows simulation of larger networks

Cooja (continued)

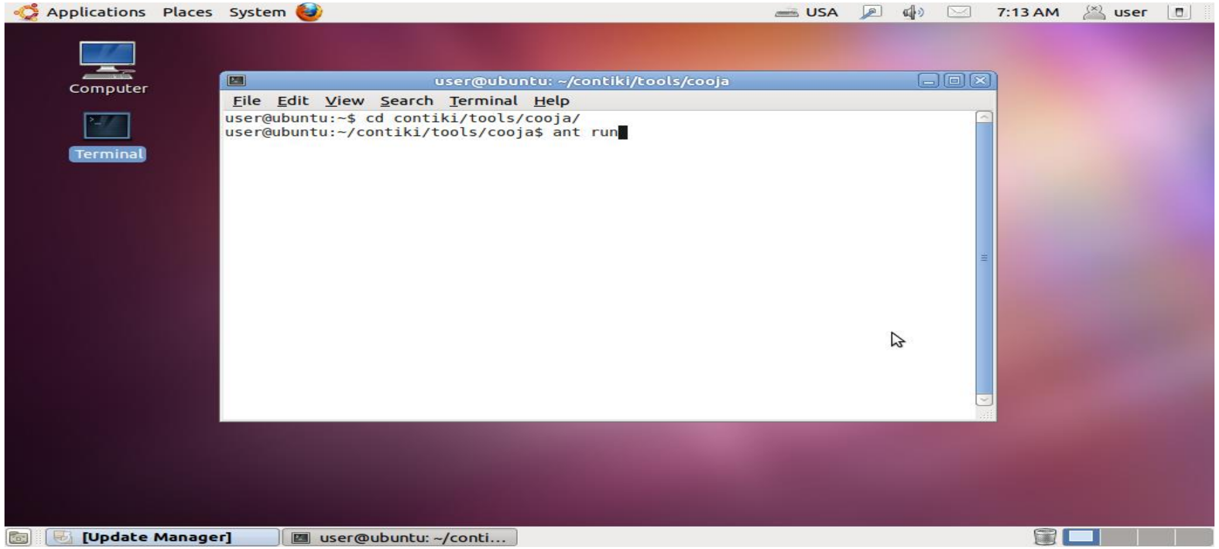
- Cooja is a highly useful tool for Contiki development
  - It allows developers to test their code and systems long before running it on the target hardware
  - Developers regularly set up new simulations to
    - debug their software
    - to verify the behaviour of their systems

Main steps

1. Open a terminal window to start Cooja
2. Create a new simulation to run Contiki in simulation and wait for Cooja to start and compile itself
3. Set simulation options
4. Create a new mote type
5. Add motes to the simulation
6. Open a terminal Cooja is a highly useful tool for Contiki development
   - It allows developers to test their code and systems long before running it on the target hardware
   - Developers regularly set up new simulations to
     1. debug their software
     2. to verify the behaviour of their systems

1. Starting Cooja

- ❑ Open a terminal window



Applications Places System
USA
7:13 AM
user
Computer
Terminal
user@ubuntu: ~/contiki/tools/cooja
File Edit View Search Terminal Help
[Update Manager]
user@ubuntu: ~/conti...

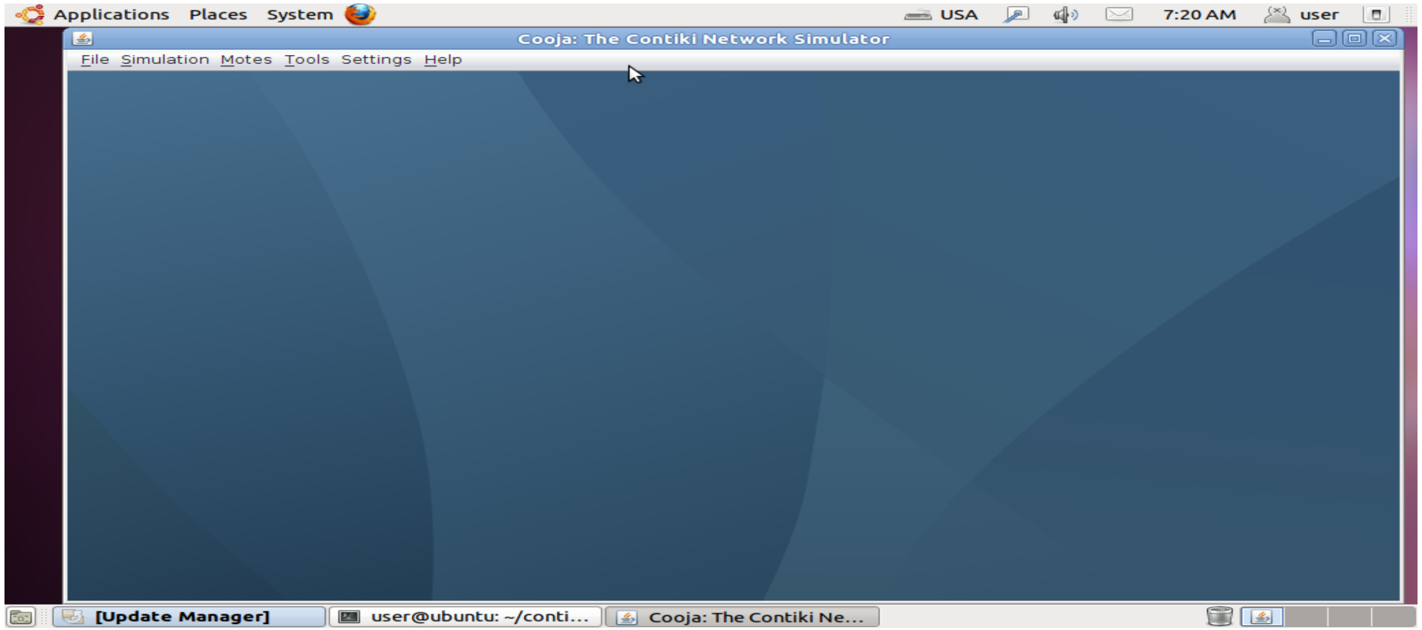
```
user@ubuntu:~$ cd contiki/tools/cooja/
user@ubuntu:~/contiki/tools/cooja$ ant run
```

To start Cooja, first **open a terminal window.**

- ✓ **cd contiki/tools/cooja** (**Cooja directory**)
- ✓ start cooja by issuing **ant run**

Waiting for Cooja to start

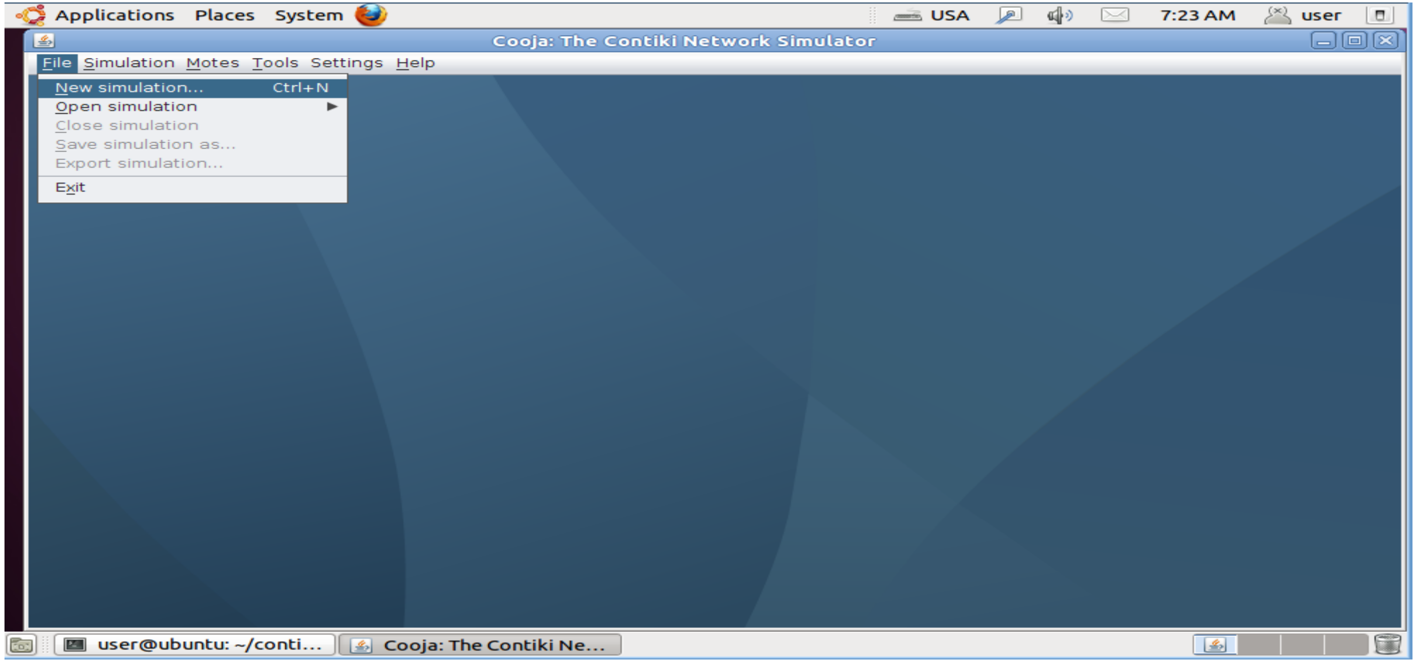
- When Cooja first starts, it will compile itself. This may take some time



When Cooja is compiled, it will start with a blue empty window.

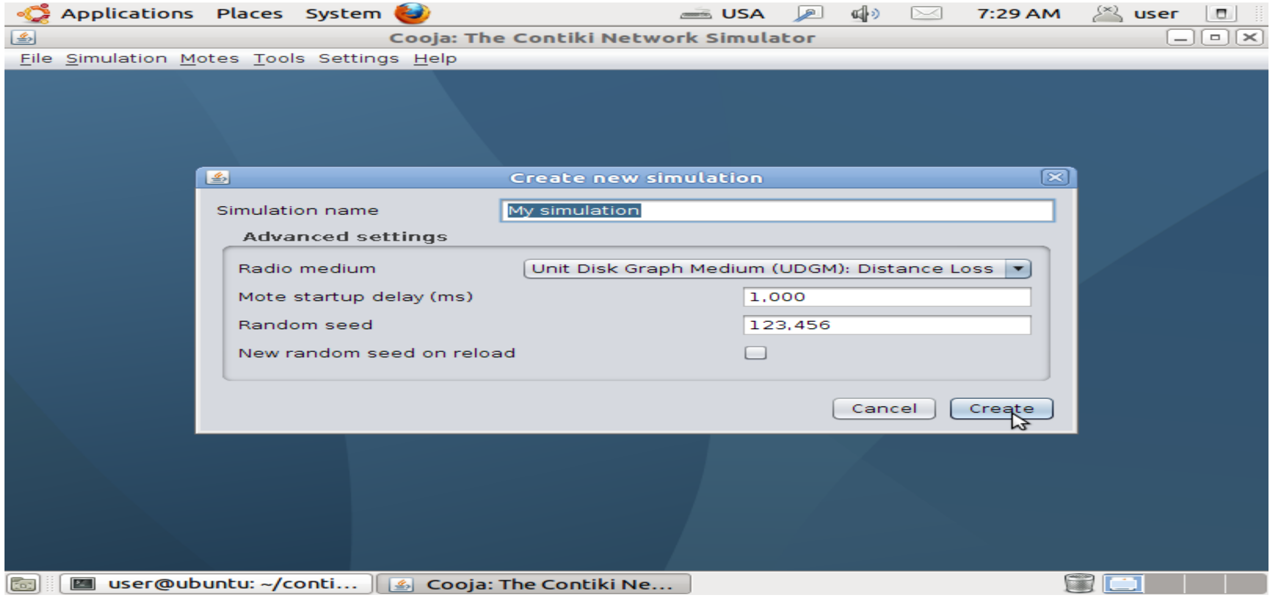
2. Create a new simulation

- Click the **File** menu and click **New simulation...**



3. Set simulation options

- Cooja now opens up the **Create new simulation** dialog. Either change the dialog name or stick with My simulation.


Applications Places System
USA 7:29 AM user
Cooja: The Contiki Network Simulator
File Simulation Motes Tools Settings Help
Create new simulation
Cancel
Create
user@ubuntu: ~/conti...
Cooja: The Contiki Ne...

Simulation name: My simulation

Advanced settings

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

Mote startup delay (ms): 1,000

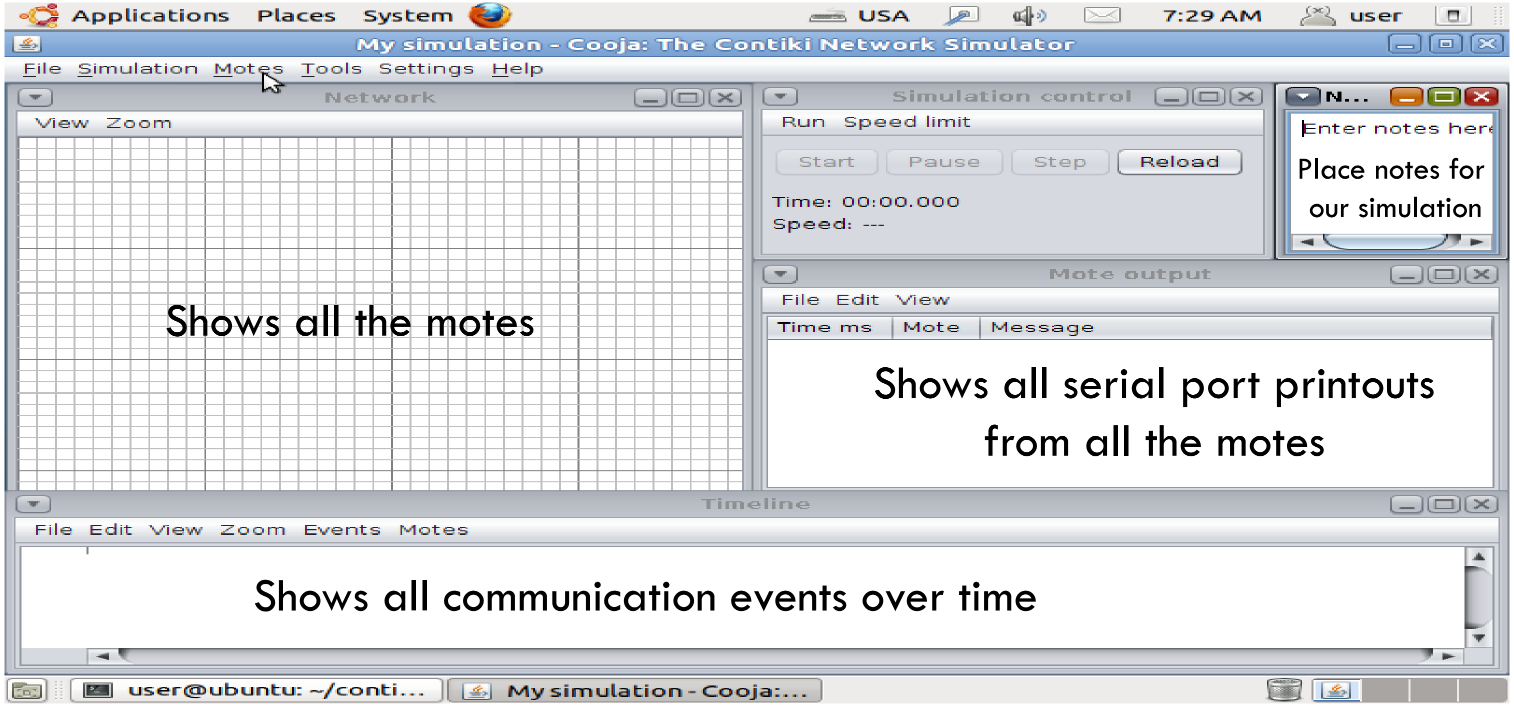
Random seed: 123,456

New random seed on reload: ☐

✓ Click the **Create** button.

Simulation windows

- Cooja brings up the new simulation.



Shows all the motes

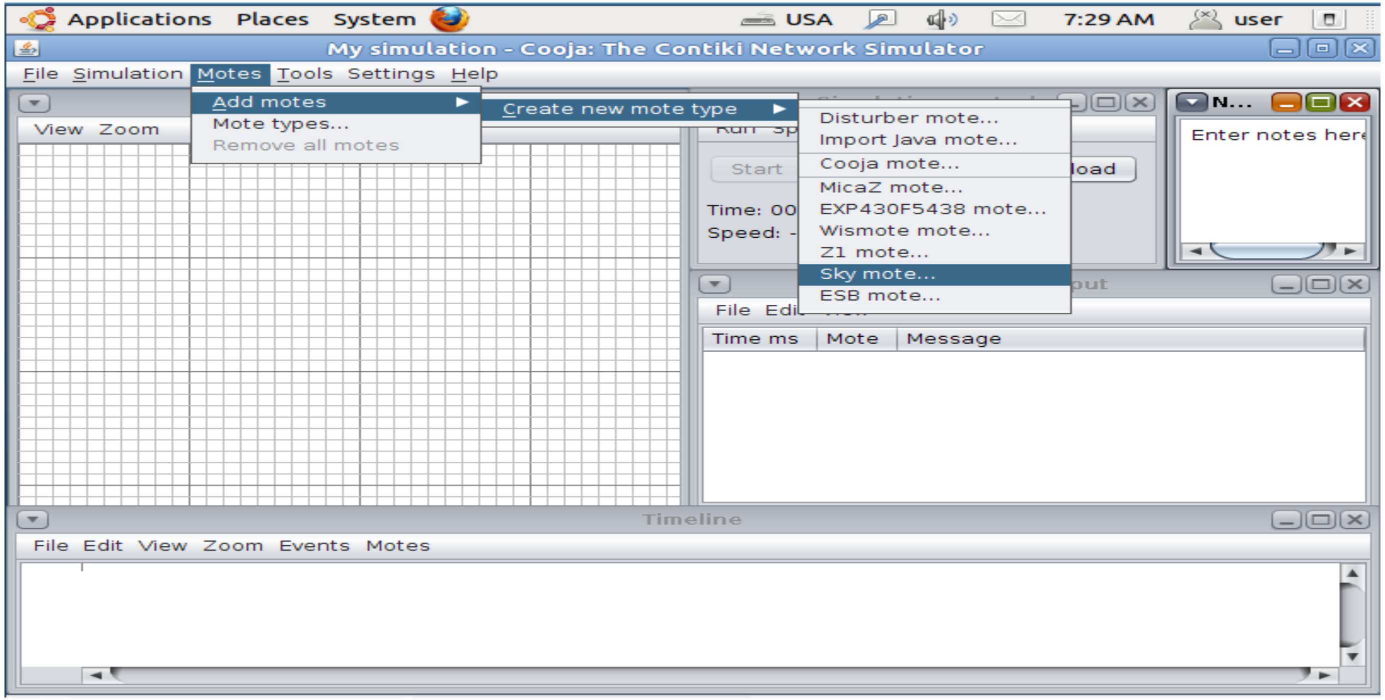
Place notes for our simulation

Shows all serial port printouts from all the motes

Shows all communication events over time

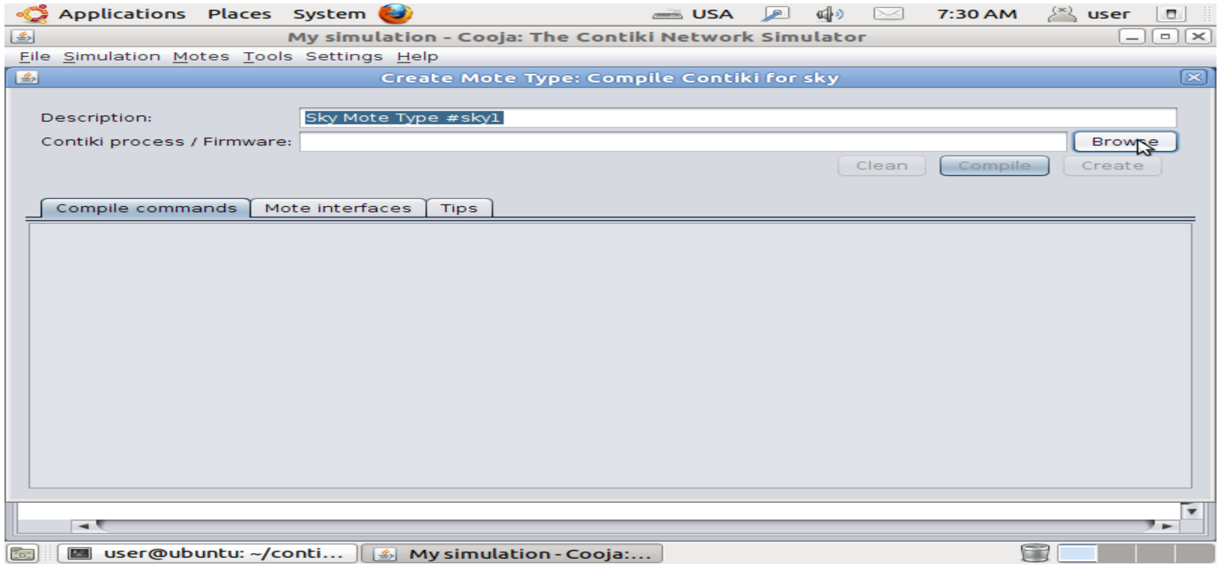
4. Add motes to the simulation

- Add motes



Create a new mote type

- ❑ Cooja opens up the **Create Mote Type** dialog

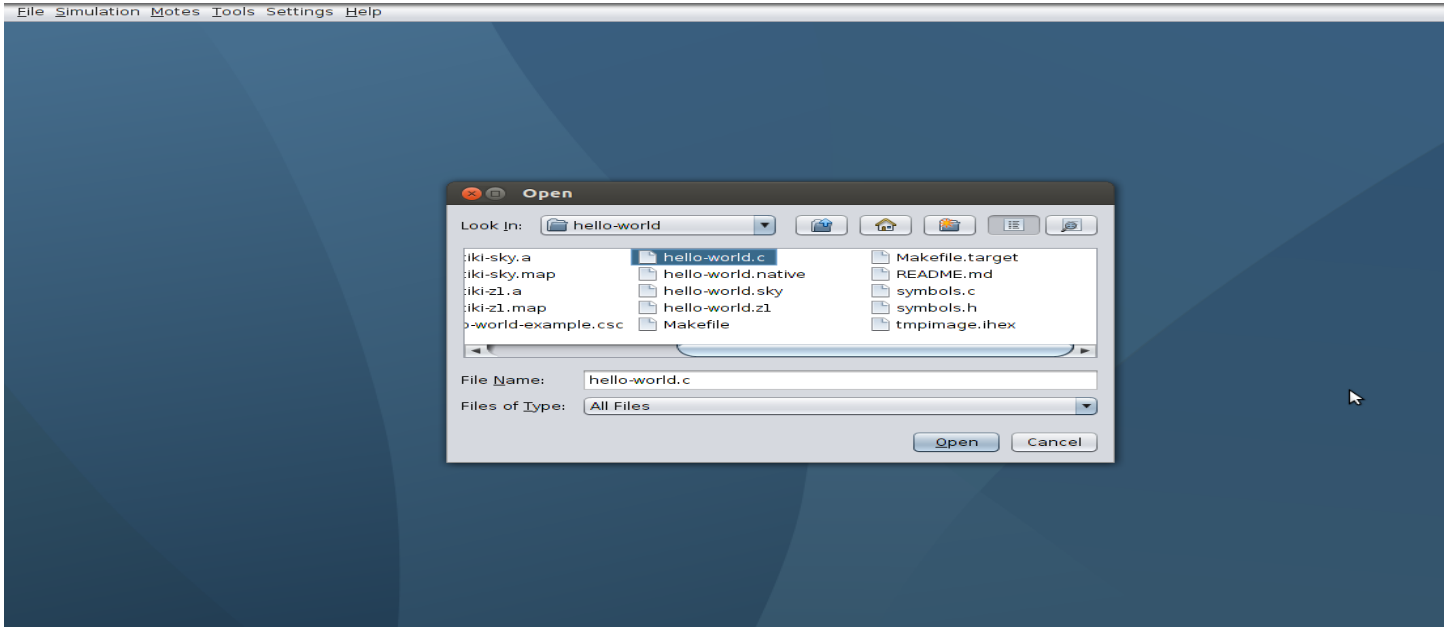

Applications Places System
USA 7:30 AM user
My simulation - Cooja: The Contiki Network Simulator
File Simulation Motes Tools Settings Help
Create Mote Type: Compile Contiki for sky
Browse
Clean
Compile
Create
Compile commands
Mote interfaces
Tips
user@ubuntu: ~/conti...
My simulation - Cooja:...

Description: Sky Mote Type #sky1
Contiki process / Firmware:

- ✓ choose a name for our mote type
- ✓ choose the Contiki application that our mote type will run

5. Find Contiki Application

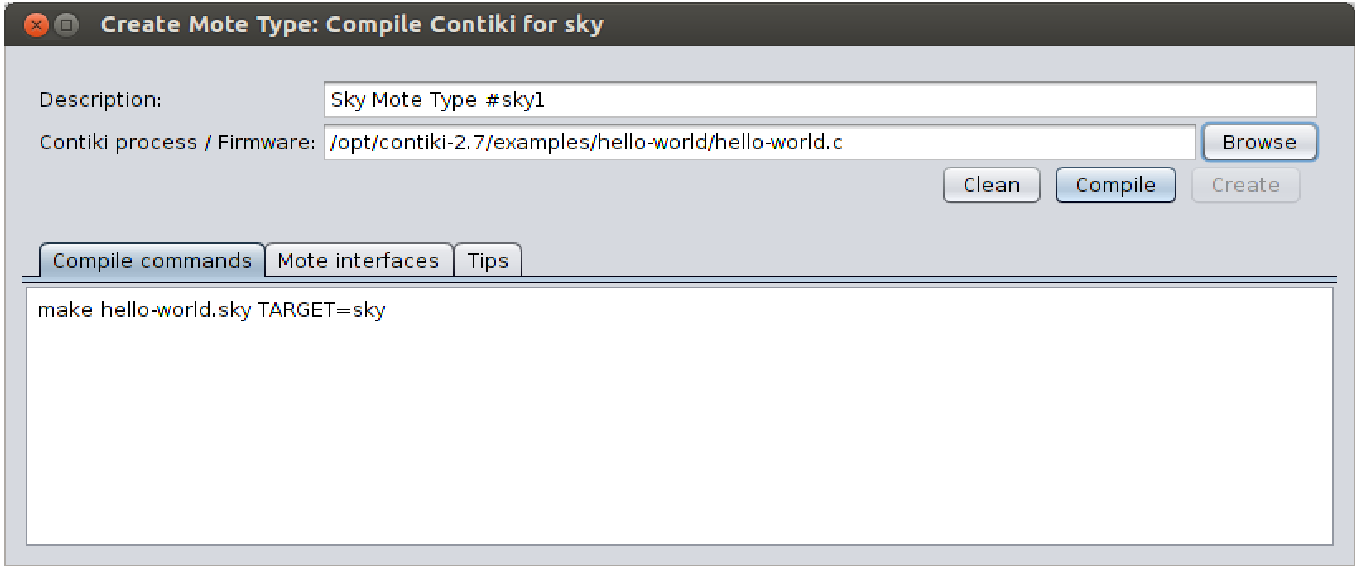
- Hello World /opt/contiki-2.7/examples/hello-world



✓ Specify application C source file → **Open**

6. Compile the Contiki application

- Cooja will verify that the selected Contiki application compiles for the platform that we have selected



Description: Sky Mote Type #sky1

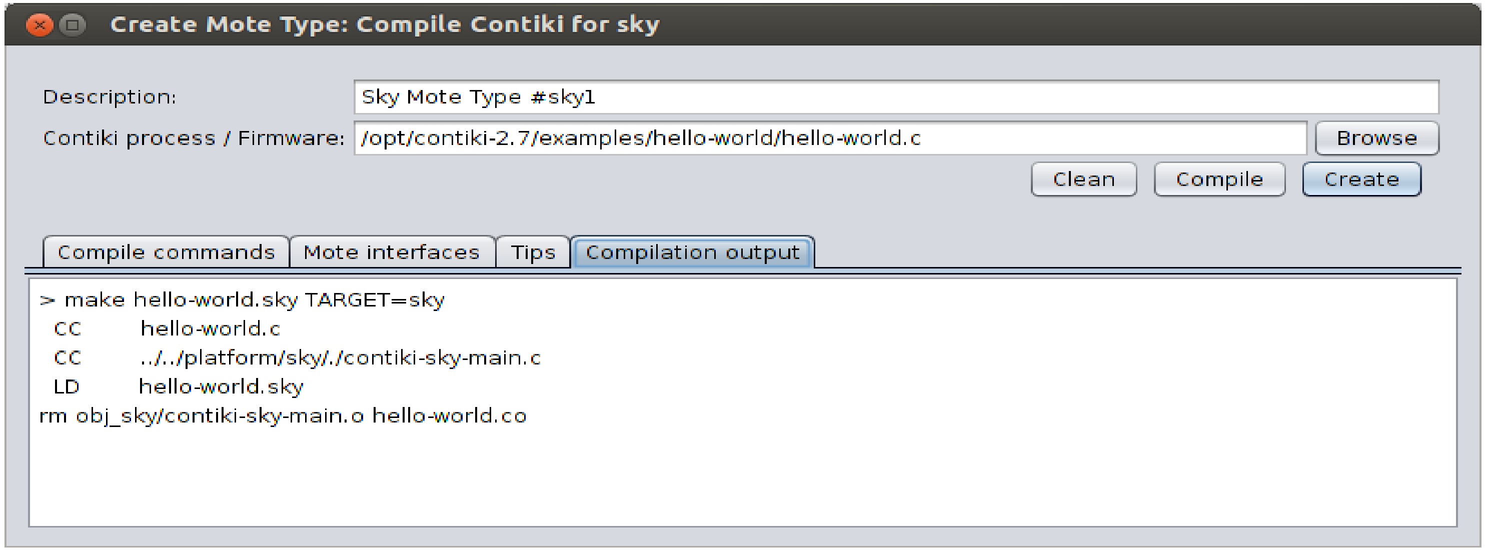
Contiki process / Firmware: /opt/contiki-2.7/examples/hello-world/hello-world.c

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

- ✓ Click on the **Compile** button. This will take some time…
- ✓ Compilation output will show up in the bottom white panel.

7. Create the mote type

- Click on the **Create** button to create the mote type. The window will close.



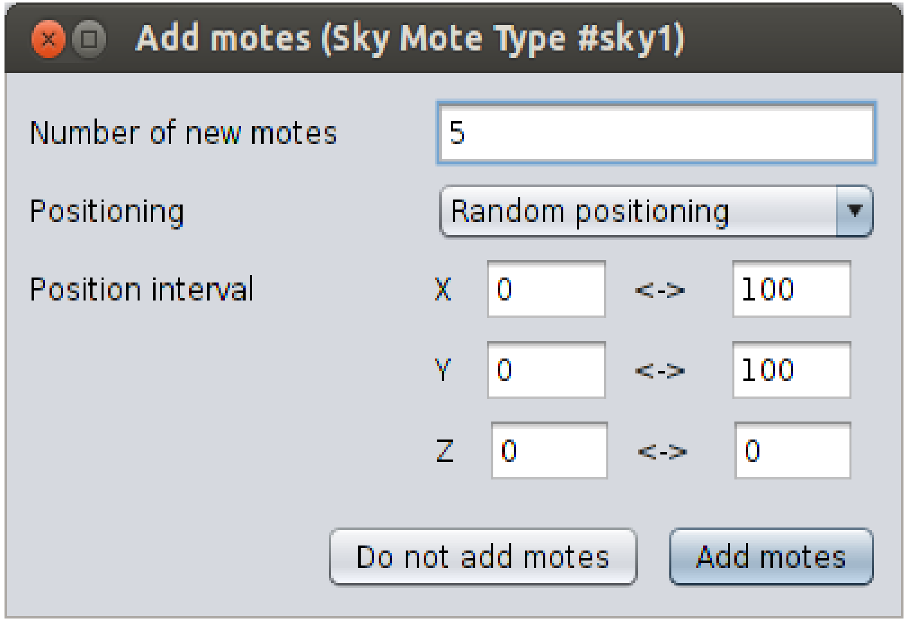
Description: Sky Mote Type #sky1

Contiki process / Firmware: /opt/contiki-2.7/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 obj_sky/contiki-sky-main.o hello-world.co
```

8. Add motes to simulation

- Add motes by changing the number of motes in the **Number of motes** field to 5.



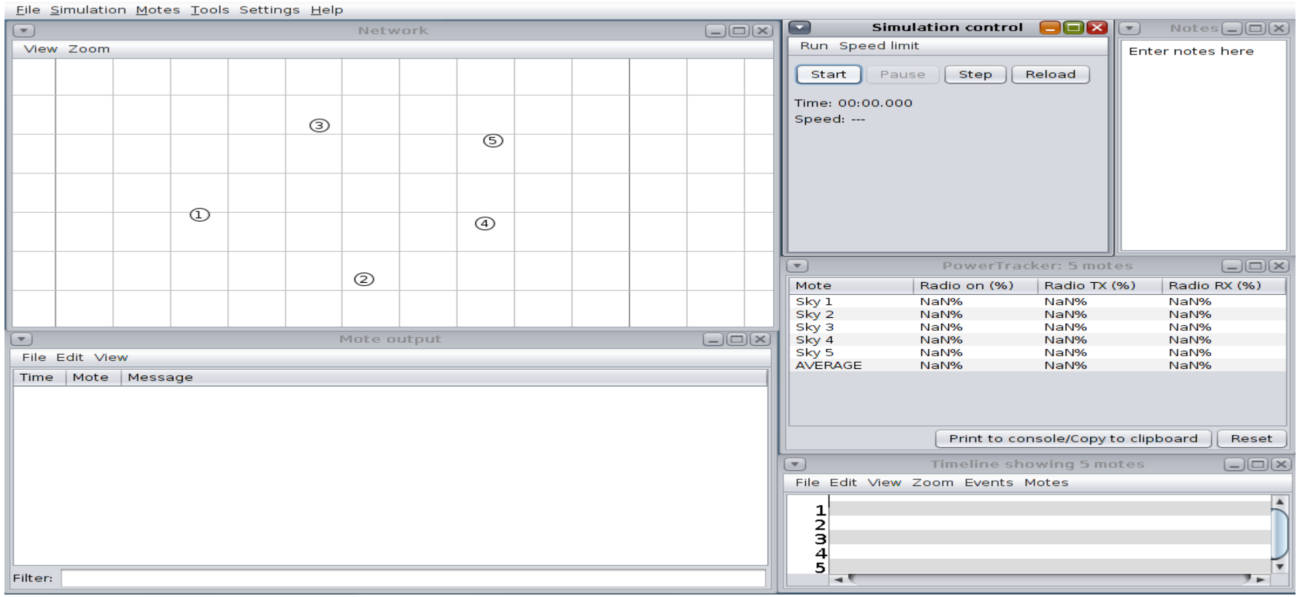
Add motes (Sky Mote Type #sky1)

Number of new motes	5			
Positioning	Random positioning			
Position interval	X	0	<->	100
	Y	0	<->	100
	Z	0	<->	0

✓ Click on **Add motes** to add motes to the simulation

9. Start the simulation

- The 5 added motes are now seen in the simulation window.



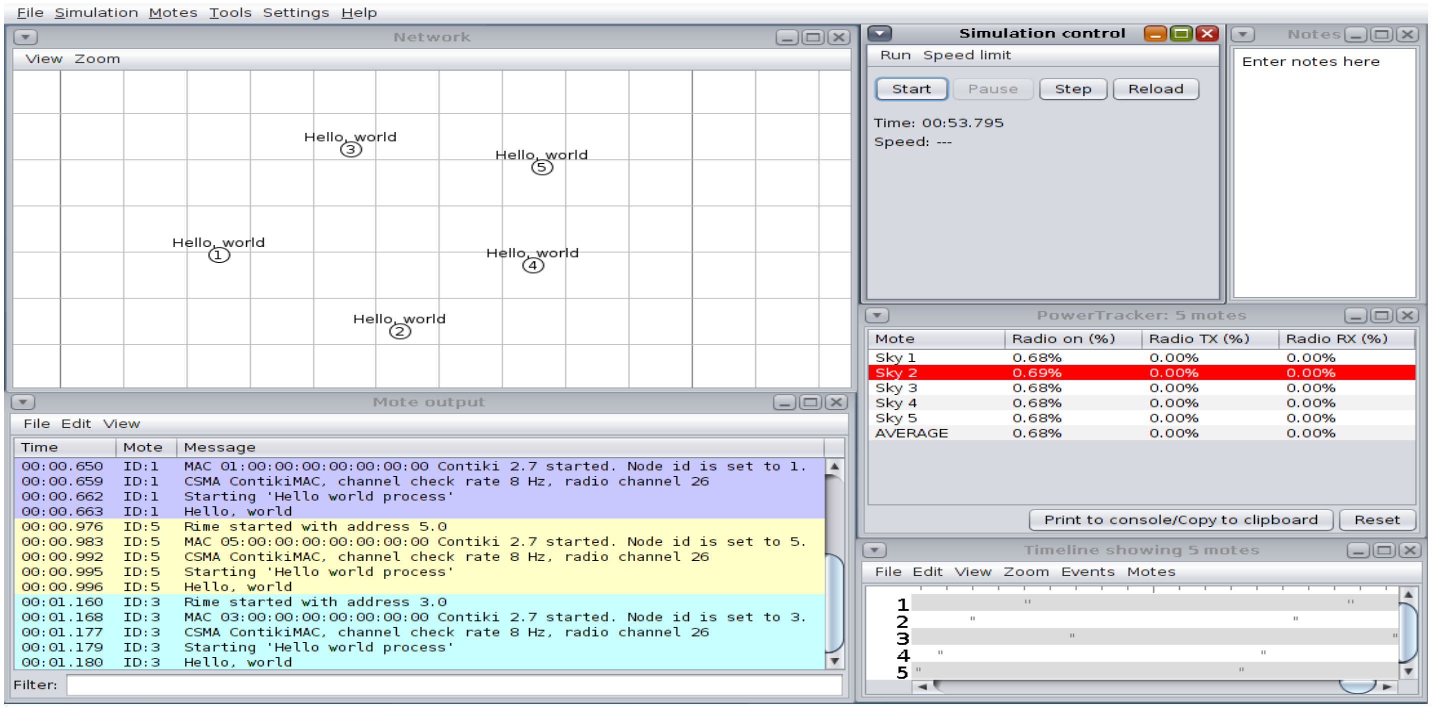
Time: 00:00.000
Speed: ---

Time	Mote	Message

Mote	Radio on (%)	Radio TX (%)	Radio RX (%)
Sky 1	NaN%	NaN%	NaN%
Sky 2	NaN%	NaN%	NaN%
Sky 3	NaN%	NaN%	NaN%
Sky 4	NaN%	NaN%	NaN%
Sky 5	NaN%	NaN%	NaN%
AVERAGE	NaN%	NaN%	NaN%

✓ Click the **Start** button to start the simulation.

10. Pause the simulation



Time: 00:53.795
Speed: ---

Mote	Radio on (%)	Radio TX (%)	Radio RX (%)
Sky 1	0.68%	0.00%	0.00%
Sky 2	0.69%	0.00%	0.00%
Sky 3	0.68%	0.00%	0.00%
Sky 4	0.68%	0.00%	0.00%
Sky 5	0.68%	0.00%	0.00%
AVERAGE	0.68%	0.00%	0.00%

```
Time       Mote   Message
00:00.650  ID:1   MAC 01:00:00:00:00:00:00:00 Contiki 2.7 started. Node id is set to 1.
00:00.659  ID:1   CSMA ContikiMAC, channel check rate 8 Hz, radio channel 26
00:00.662  ID:1   Starting 'Hello world process'
00:00.663  ID:1   Hello, world
00:00.976  ID:5   Rime started with address 5.0
00:00.983  ID:5   MAC 05:00:00:00:00:00:00:00 Contiki 2.7 started. Node id is set to 5.
00:00.992  ID:5   CSMA ContikiMAC, channel check rate 8 Hz, radio channel 26
00:00.995  ID:5   Starting 'Hello world process'
00:00.996  ID:5   Hello, world
00:01.160  ID:3   Rime started with address 3.0
00:01.168  ID:3   MAC 03:00:00:00:00:00:00:00 Contiki 2.7 started. Node id is set to 3.
00:01.177  ID:3   CSMA ContikiMAC, channel check rate 8 Hz, radio channel 26
00:01.179  ID:3   Starting 'Hello world process'
00:01.180  ID:3   Hello, world
```

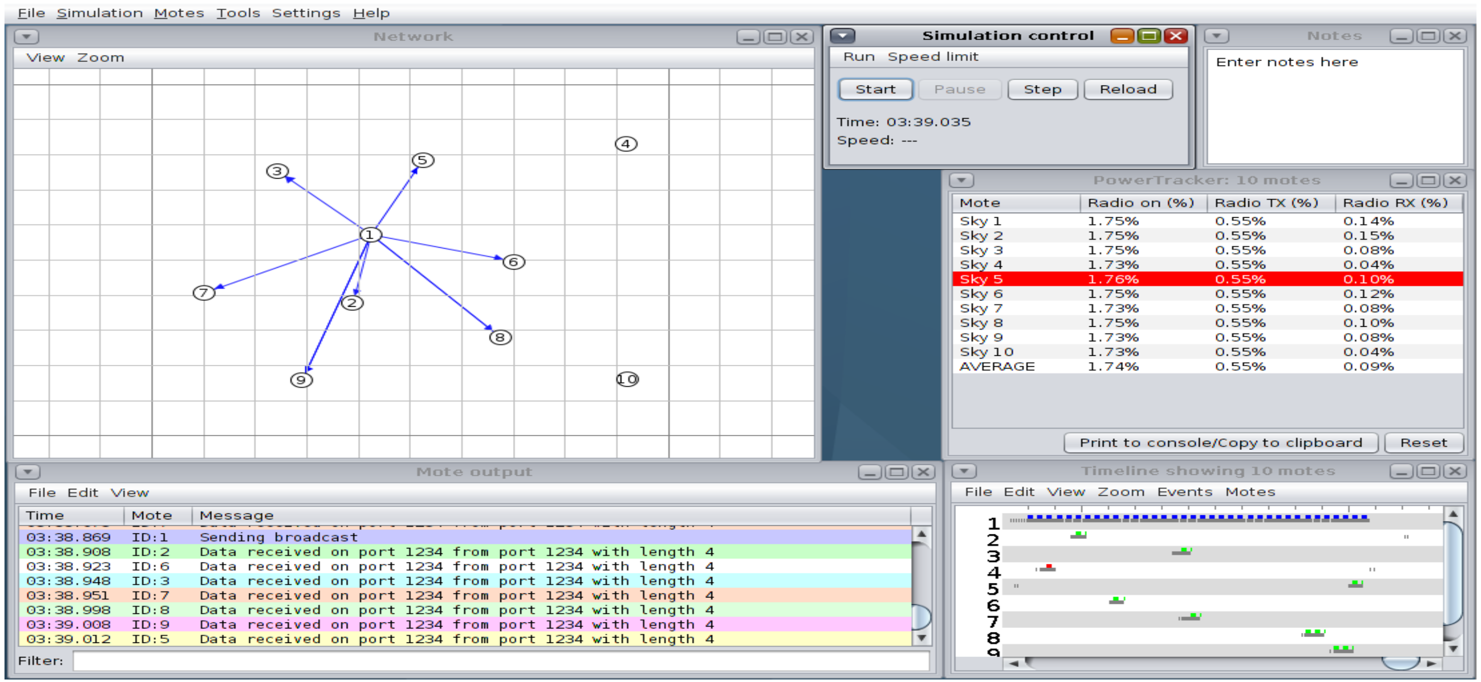
- ✓ **View** → Select Log output: printf()'s

11. Get some statistics

- Mote output window
  - Printouts from the simulated motes
- Network window
  - Shows ongoing network communication
- Timeline
  - Shows communication and radio events over time
  - The small gray lines are ContikiMAC periodically waking up the radio
- Pause
  - Click the **Pause** button to pause the simulation

More examples

- simple-udp-rpl/broadcast-example.c



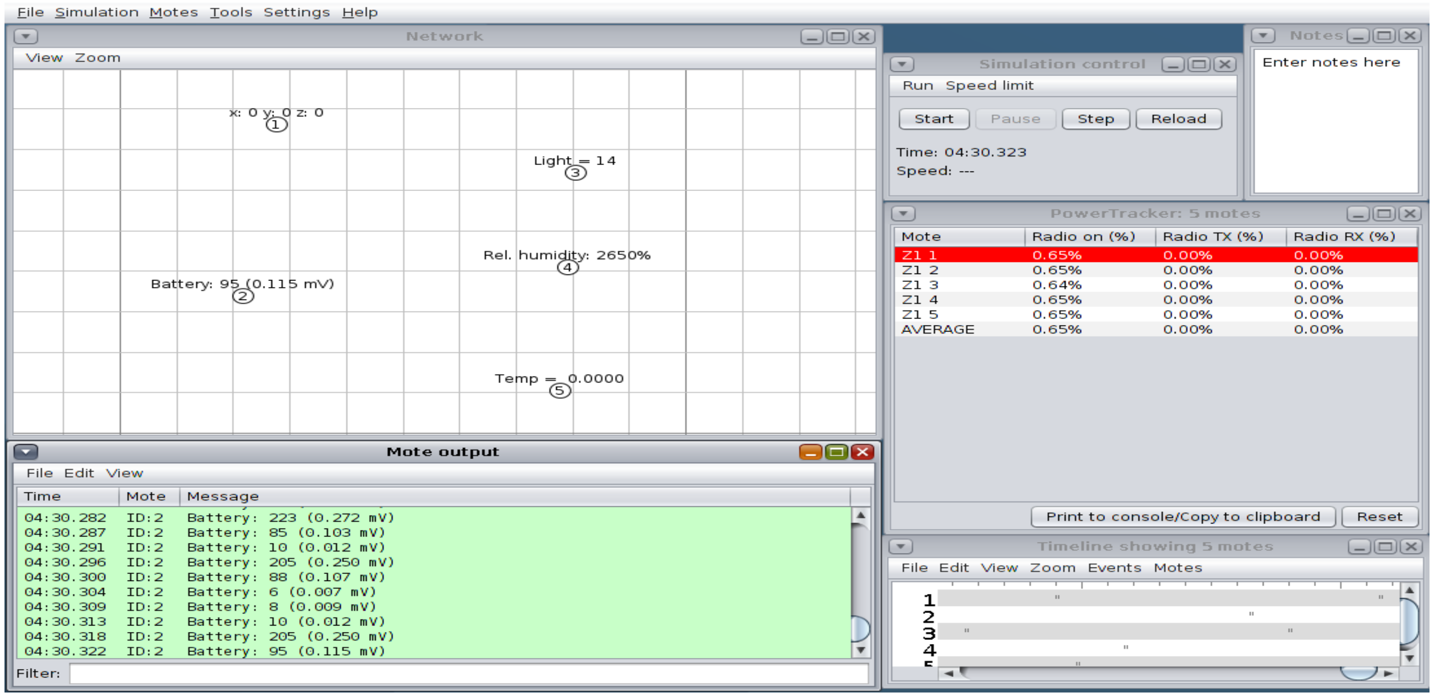
Time: 03:39.035
Speed: ---

Mote	Radio on (%)	Radio TX (%)	Radio RX (%)
Sky 1	1.75%	0.55%	0.14%
Sky 2	1.75%	0.55%	0.15%
Sky 3	1.75%	0.55%	0.08%
Sky 4	1.73%	0.55%	0.04%
Sky 5	1.76%	0.55%	0.10%
Sky 6	1.75%	0.55%	0.12%
Sky 7	1.73%	0.55%	0.08%
Sky 8	1.75%	0.55%	0.10%
Sky 9	1.73%	0.55%	0.08%
Sky 10	1.73%	0.55%	0.04%
AVERAGE	1.74%	0.55%	0.09%

```
Time       Mote   Message
03:38.869  ID:1   Sending broadcast
03:38.908  ID:2   Data received on port 1234 from port 1234 with length 4
03:38.923  ID:6   Data received on port 1234 from port 1234 with length 4
03:38.948  ID:3   Data received on port 1234 from port 1234 with length 4
03:38.951  ID:7   Data received on port 1234 from port 1234 with length 4
03:38.998  ID:8   Data received on port 1234 from port 1234 with length 4
03:39.008  ID:9   Data received on port 1234 from port 1234 with length 4
03:39.012  ID:5   Data received on port 1234 from port 1234 with length 4
```

More examples

- Z1 sensors



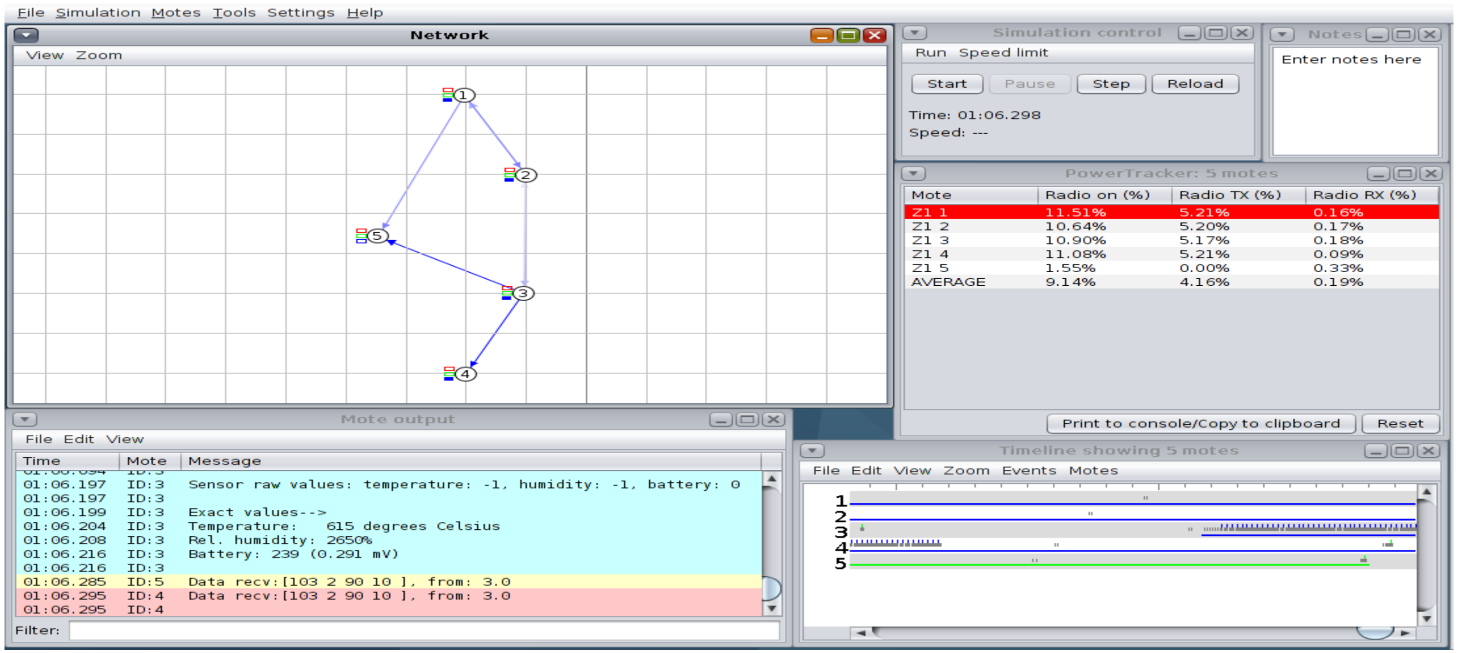
```
Time: 04:30.323
Speed: ---
```

Mote	Radio on (%)	Radio TX (%)	Radio RX (%)
Z1 1	0.65%	0.00%	0.00%
Z1 2	0.65%	0.00%	0.00%
Z1 3	0.64%	0.00%	0.00%
Z1 4	0.65%	0.00%	0.00%
Z1 5	0.65%	0.00%	0.00%
AVERAGE	0.65%	0.00%	0.00%

```
Time       Mote  Message
04:30.282  ID:2  Battery: 223 (0.272 mV)
04:30.287  ID:2  Battery: 85 (0.103 mV)
04:30.291  ID:2  Battery: 10 (0.012 mV)
04:30.296  ID:2  Battery: 205 (0.250 mV)
04:30.300  ID:2  Battery: 88 (0.107 mV)
04:30.304  ID:2  Battery: 6 (0.007 mV)
04:30.309  ID:2  Battery: 8 (0.009 mV)
04:30.313  ID:2  Battery: 10 (0.012 mV)
04:30.318  ID:2  Battery: 205 (0.250 mV)
04:30.322  ID:2  Battery: 95 (0.115 mV)
```

More examples

- Sense, send and blink with receive and blink



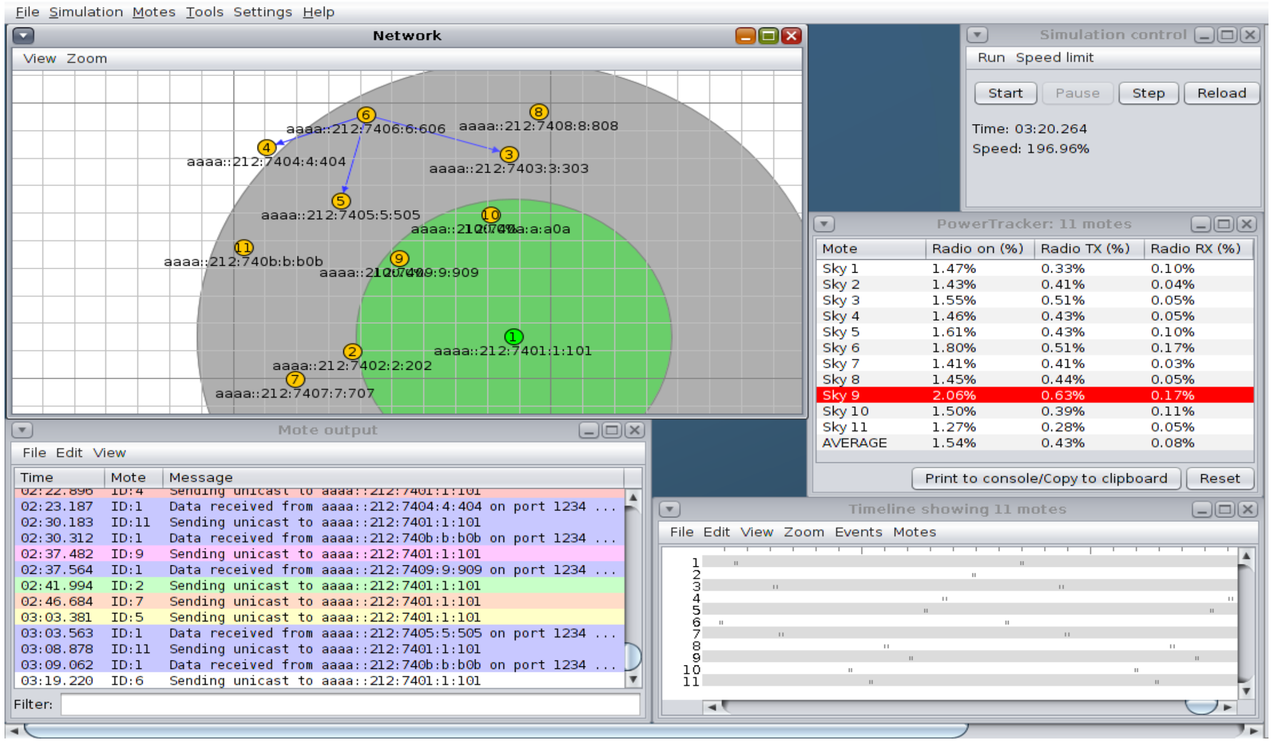
Time: 01:06.298
Speed: ---

Mote	Radio on (%)	Radio TX (%)	Radio RX (%)
Z1 1	11.51%	5.21%	0.16%
Z1 2	10.64%	5.20%	0.17%
Z1 3	10.90%	5.17%	0.18%
Z1 4	11.08%	5.21%	0.09%
Z1 5	1.55%	0.00%	0.33%
AVERAGE	9.14%	4.16%	0.19%

```
Time        Mote   Message
01:06.197   ID:3   Sensor raw values: temperature: -1, humidity: -1, battery: 0
01:06.197   ID:3
01:06.199   ID:3   Exact values-->
01:06.204   ID:3   Temperature:   615 degrees Celsius
01:06.208   ID:3   Rel. humidity: 2650%
01:06.216   ID:3   Battery: 239 (0.291 mV)
01:06.216   ID:3
01:06.285   ID:5   Data recv:[103 2 90 10 ], from: 3.0
01:06.295   ID:4   Data recv:[103 2 90 10 ], from: 3.0
01:06.295   ID:4
```

More examples

- unicast-example.c
  - ipv6
  - simple-udp-rpl



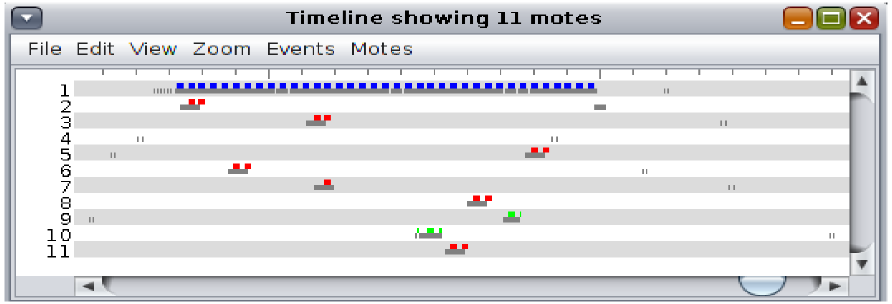
Time: 03:20.264
Speed: 196.96%

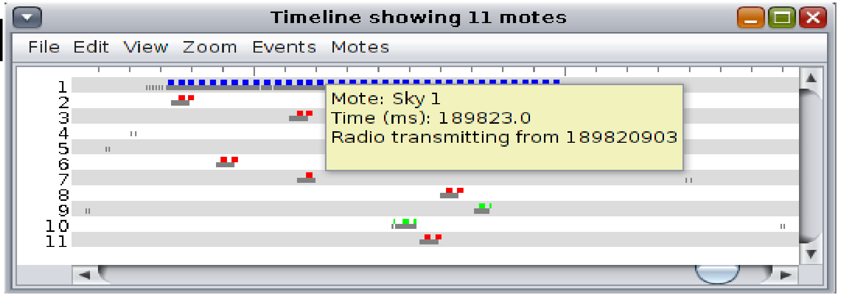
Mote	Radio on (%)	Radio TX (%)	Radio RX (%)
Sky 1	1.47%	0.33%	0.10%
Sky 2	1.43%	0.41%	0.04%
Sky 3	1.55%	0.51%	0.05%
Sky 4	1.46%	0.43%	0.05%
Sky 5	1.61%	0.43%	0.10%
Sky 6	1.80%	0.51%	0.17%
Sky 7	1.41%	0.41%	0.03%
Sky 8	1.45%	0.44%	0.05%
Sky 9	2.06%	0.63%	0.17%
Sky 10	1.50%	0.39%	0.11%
Sky 11	1.27%	0.28%	0.05%
AVERAGE	1.54%	0.43%	0.08%

```
Time       Mote   Message
02:22.896  ID:4   Sending unicast to aaaa::212:7401:1:101
02:23.187  ID:1   Data received from aaaa::212:7404:4:404 on port 1234 ...
02:30.183  ID:11  Sending unicast to aaaa::212:7401:1:101
02:30.312  ID:1   Data received from aaaa::212:740b:b:b0b on port 1234 ...
02:37.482  ID:9   Sending unicast to aaaa::212:7401:1:101
02:37.564  ID:1   Data received from aaaa::212:7409:9:909 on port 1234 ...
02:41.994  ID:2   Sending unicast to aaaa::212:7401:1:101
02:46.684  ID:7   Sending unicast to aaaa::212:7401:1:101
03:03.381  ID:5   Sending unicast to aaaa::212:7401:1:101
03:03.563  ID:1   Data received from aaaa::212:7405:5:505 on port 1234 ...
03:08.878  ID:11  Sending unicast to aaaa::212:7401:1:101
03:09.062  ID:1   Data received from aaaa::212:740b:b:b0b on port 1234 ...
03:19.220  ID:6   Sending unicast to aaaa::212:7401:1:101
```

Timeline in COOJA

- Radio ON/OFF
  - No colour: radio off
  - Grey: radio on
- Radio RX/TX
  - Green: received a packet
  - Blue: packet sent
  - Red: interfered radio (collisions etc.)
- Right-clicking will reveal additional info.[2]





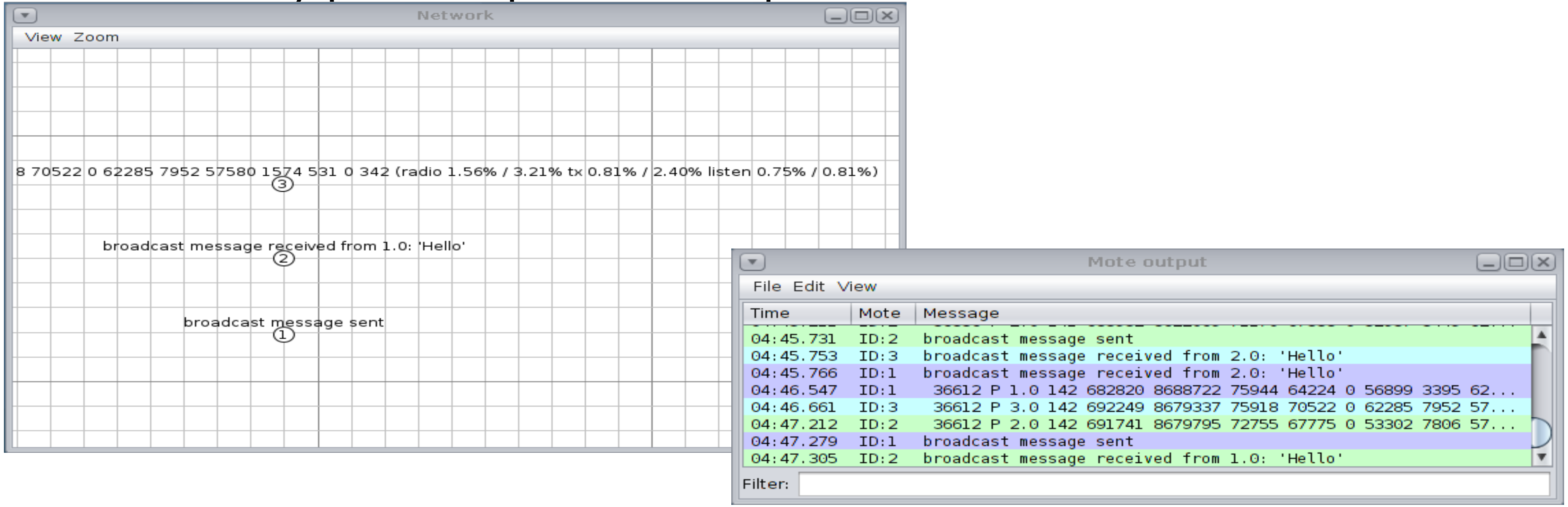
Mote: Sky 1
Time (ms): 189823.0
Radio transmitting from 189820903

Measure Power Consumption with Energest

- Can be used for obtaining per-component power consumption on Contiki.
  - (cpu_ON, LPM, TX, RX)
  - i.e. the time the radio was in RX mode (rxon)
- For RX:
  - Power(mW) = (rxend – rxstart) * 20mA * 3V / 4096 / runtime(seconds)
  - If you do not divide by runtime you get the energy consumption during runtime.

Measure Power Consumption: Powertrace

- Uses Energest along with a periodic difference of the rtimer ticks to get average power over a shorter period of time or for particular network modes[3].
- Periodically prints out power consumption

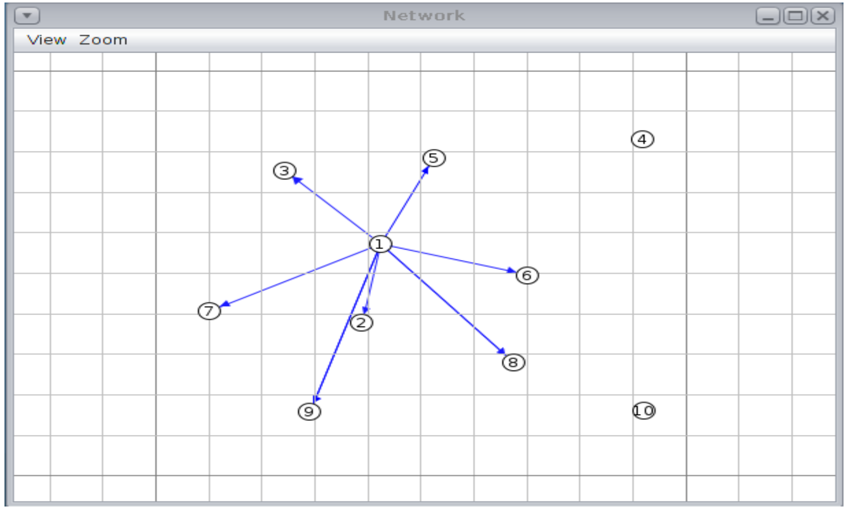


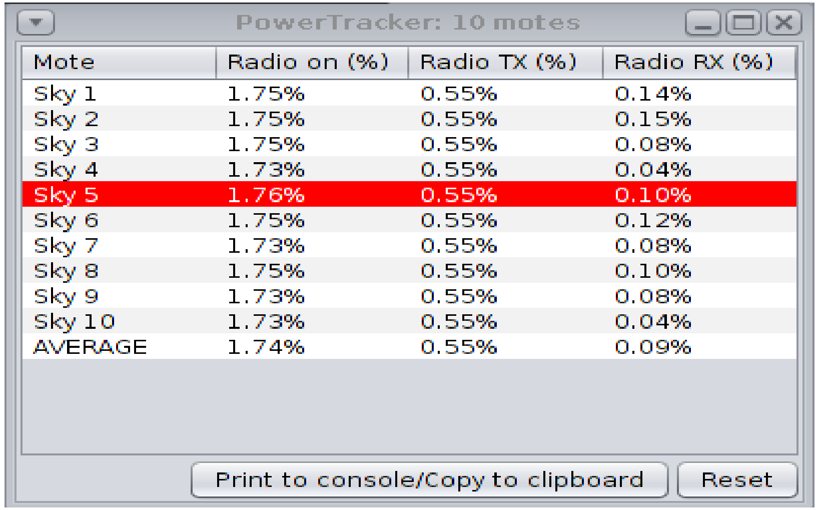
```
8 70522 0 62285 7952 57580 1574 531 0 342 (radio 1.56% / 3.21% tx 0.81% / 2.40% listen 0.75% / 0.81%)
broadcast message received from 1.0: 'Hello'
broadcast message sent
```

```
Time        Mote   Message
04:45.731   ID:2   broadcast message sent
04:45.753   ID:3   broadcast message received from 2.0: 'Hello'
04:45.766   ID:1   broadcast message received from 2.0: 'Hello'
04:46.547   ID:1    36612 P 1.0 142 682820 8688722 75944 64224 0 56899 3395 62...
04:46.661   ID:3    36612 P 3.0 142 692249 8679337 75918 70522 0 62285 7952 57...
04:47.212   ID:2    36612 P 2.0 142 691741 8679795 72755 67775 0 53302 7806 57...
04:47.279   ID:1   broadcast message sent
04:47.305   ID:2   broadcast message received from 1.0: 'Hello'
```

Measure Power Consumption: PowerTracker

- A COOJA plugin that measures the average simulated radio duty cycles.
  - ✓ simple-udp-rpl/broadcast-example.c





Mote	Radio on (%)	Radio TX (%)	Radio RX (%)
Sky 1	1.75%	0.55%	0.14%
Sky 2	1.75%	0.55%	0.15%
Sky 3	1.75%	0.55%	0.08%
Sky 4	1.73%	0.55%	0.04%
Sky 5	1.76%	0.55%	0.10%
Sky 6	1.75%	0.55%	0.12%
Sky 7	1.73%	0.55%	0.08%
Sky 8	1.75%	0.55%	0.10%
Sky 9	1.73%	0.55%	0.08%
Sky 10	1.73%	0.55%	0.04%
AVERAGE	1.74%	0.55%	0.09%

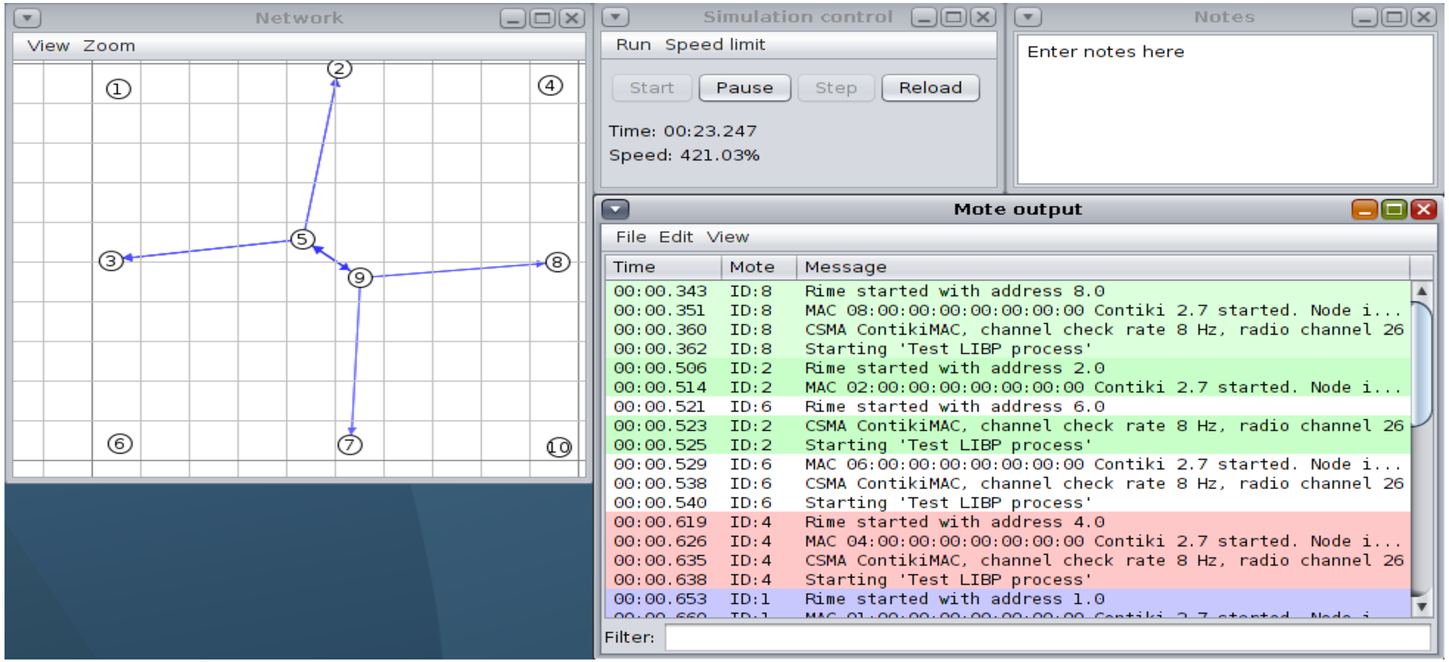
Network Protocols

- COOJA has 2 stacks: uIP and Rime
- Protocol stacks may be interconnected
  - uIP data can be transmitted over Rime and vice versa
- Cooja can be used to emulate network protocols:
  - RPL
  - LIBP

Introduction to LIBP

- LIBP, known as the **Least Interference Beaconing Protocol**, is the implementation of the **Least Interference Beaconing Algorithm, LIBA.**
- LIBP extends the beaconing process widely used by collection protocols with load balancing to improve the Ubiquitous Sensor Network (USN) energy efficiency[4].
- The process involving the least interference paradigm allows the selection of a parent node that has the smallest number of children. This is a point of least traffic flow interference.
- The parent selection model chooses the first parent node heard from, whereby the sensor nodes hear from a set of neighbours and select the least burdened (in number of children) as the parent node.

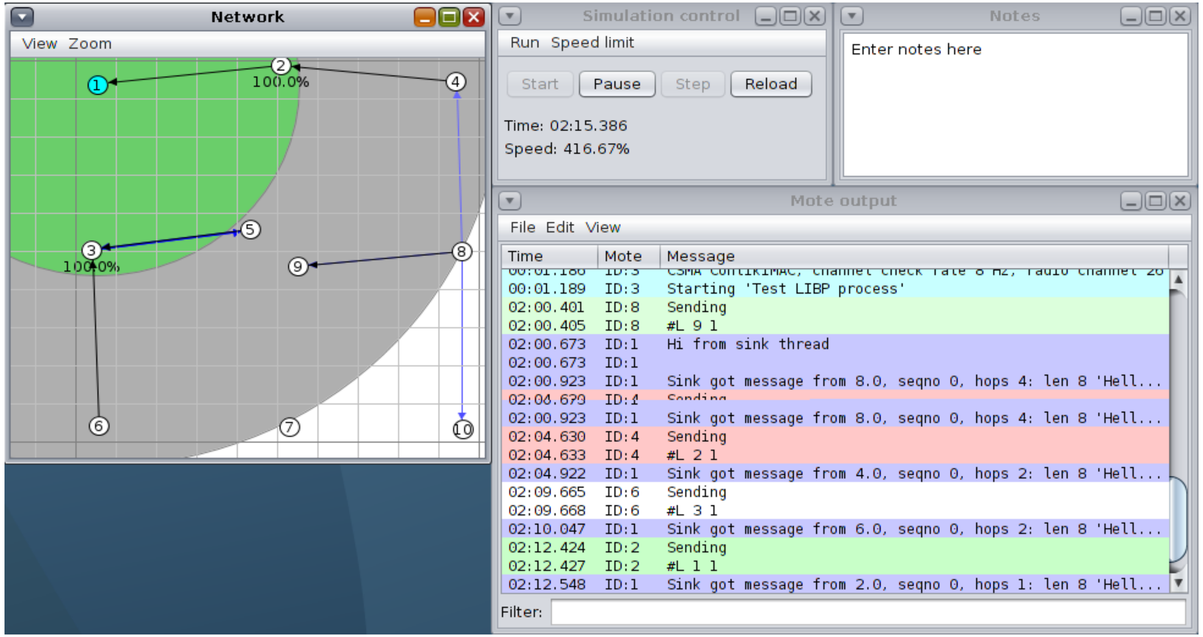
LIBP – Rime startup



```
Time       Mote   Message
00:00.343  ID:8   Rime started with address 8.0
00:00.351  ID:8   MAC 08:00:00:00:00:00:00:00 Contiki 2.7 started. Node i...
00:00.360  ID:8   CSMA ContikiMAC, channel check rate 8 Hz, radio channel 26
00:00.362  ID:8   Starting 'Test LIBP process'
00:00.506  ID:2   Rime started with address 2.0
00:00.514  ID:2   MAC 02:00:00:00:00:00:00:00 Contiki 2.7 started. Node i...
00:00.521  ID:6   Rime started with address 6.0
00:00.523  ID:2   CSMA ContikiMAC, channel check rate 8 Hz, radio channel 26
00:00.525  ID:2   Starting 'Test LIBP process'
00:00.529  ID:6   MAC 06:00:00:00:00:00:00:00 Contiki 2.7 started. Node i...
00:00.538  ID:6   CSMA ContikiMAC, channel check rate 8 Hz, radio channel 26
00:00.540  ID:6   Starting 'Test LIBP process'
00:00.619  ID:4   Rime started with address 4.0
00:00.626  ID:4   MAC 04:00:00:00:00:00:00:00 Contiki 2.7 started. Node i...
00:00.635  ID:4   CSMA ContikiMAC, channel check rate 8 Hz, radio channel 26
00:00.638  ID:4   Starting 'Test LIBP process'
00:00.653  ID:1   Rime started with address 1.0
00:00.660  ID:1   MAC 01:00:00:00:00:00:00:00 Contiki 2.7 started. Node i...
```

Upon network startup, Rime started with address 8.0 for Node ID 8.
The image details the radio channel as 26 and the channel check rate of 8 Hz.

LIBP – sink mote

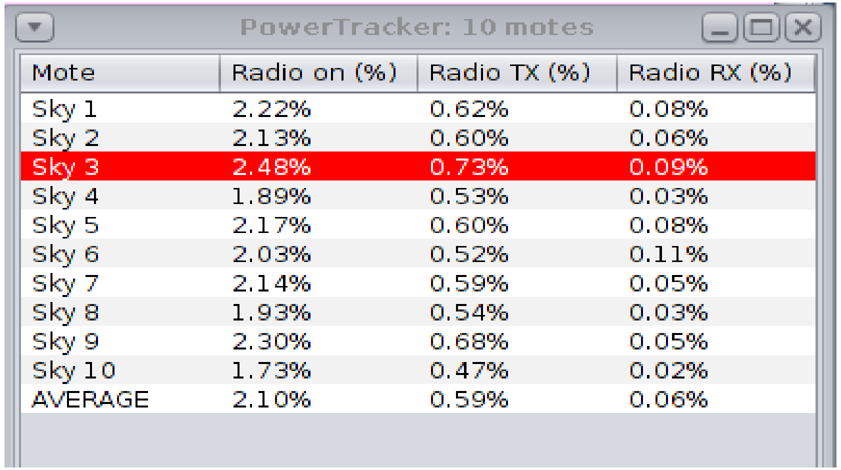


```
Time: 02:15.386
Speed: 416.67%
```

```
Time       Mote   Message
00:01.188  ID:3   CSMA ContikiMAC, channel check rate 8 Hz, radio channel 26
00:01.189  ID:3   Starting 'Test LIBP process'
02:00.401  ID:8   Sending
02:00.405  ID:8   #L 9 1
02:00.673  ID:1   Hi from sink thread
02:00.673  ID:1
02:00.923  ID:1   Sink got message from 8.0, seqno 0, hops 4: len 8 'Hell...
02:04.629  ID:4   Sending
02:00.923  ID:1   Sink got message from 8.0, seqno 0, hops 4: len 8 'Hell...
02:04.630  ID:4   Sending
02:04.633  ID:4   #L 2 1
02:04.922  ID:1   Sink got message from 4.0, seqno 0, hops 2: len 8 'Hell...
02:09.665  ID:6   Sending
02:09.668  ID:6   #L 3 1
02:10.047  ID:1   Sink got message from 6.0, seqno 0, hops 2: len 8 'Hell...
02:12.424  ID:2   Sending
02:12.427  ID:2   #L 1 1
02:12.548  ID:1   Sink got message from 2.0, seqno 0, hops 1: len 8 'Hell...
```

Sink mote with ID 1 – After 2 minutes, 0 seconds and 673 milliseconds, ID 1 broad-casted to the network that it is sink by sending “**Hi from sink thread**”.

LIBP - PowerTracker



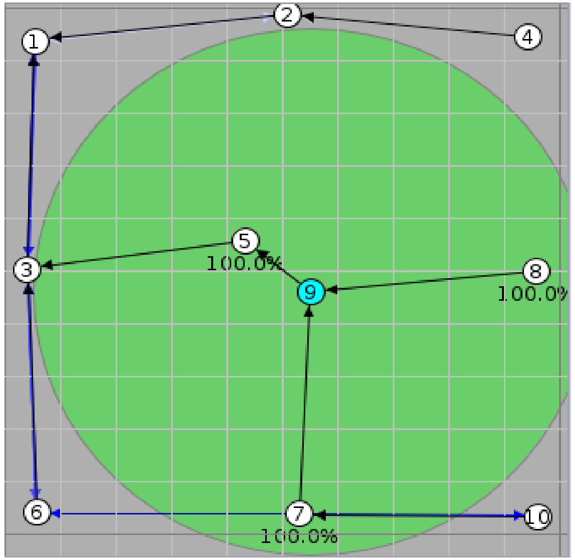
PowerTracker: 10 motes

Mote	Radio on (%)	Radio TX (%)	Radio RX (%)
Sky 1	2.22%	0.62%	0.08%
Sky 2	2.13%	0.60%	0.06%
Sky 3	2.48%	0.73%	0.09%
Sky 4	1.89%	0.53%	0.03%
Sky 5	2.17%	0.60%	0.08%
Sky 6	2.03%	0.52%	0.11%
Sky 7	2.14%	0.59%	0.05%
Sky 8	1.93%	0.54%	0.03%
Sky 9	2.30%	0.68%	0.05%
Sky 10	1.73%	0.47%	0.02%
AVERAGE	2.10%	0.59%	0.06%

PowerTracker after **5 minutes.**

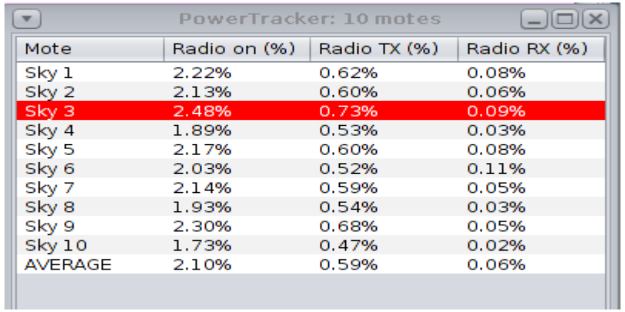
Sky 3 used the most power by being on most of the time.
It's Radio TX is also the highest with a value of **0.73%**.
It has the second highest Radio RX of **0.09%**.

LIBP – Parent with children



Node 3 has 2 children, namely nodes 5 and 6.
These nodes also have children.
Sky 10 used the **least power** with its
Radio on at 1.73%
Radio TX at 0.47% and
Radio RX of 0.02% (least percentage).

Sky 10 is ranked along the bottom of the tree, has no children and is only active when it has to send its data, unlike the other motes.



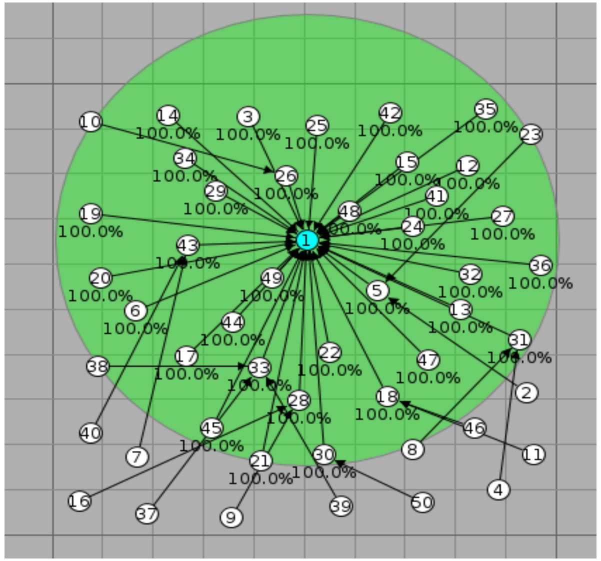
PowerTracker: 10 motes

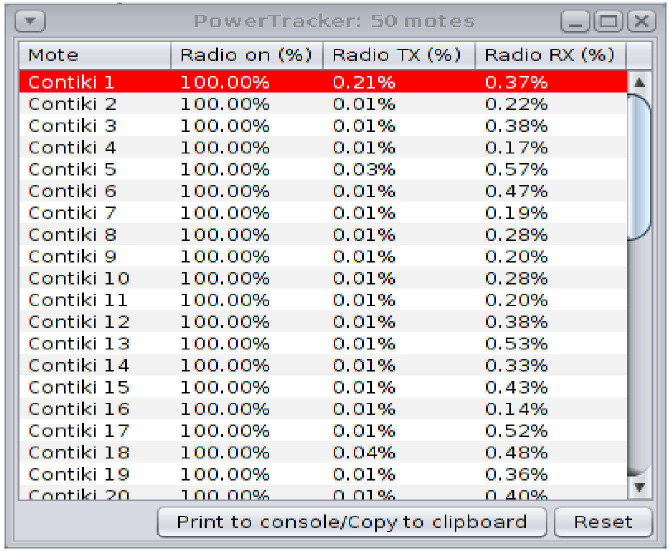
Mote	Radio on (%)	Radio TX (%)	Radio RX (%)
Sky 1	2.22%	0.62%	0.08%
Sky 2	2.13%	0.60%	0.06%
Sky 3	2.48%	0.73%	0.09%
Sky 4	1.89%	0.53%	0.03%
Sky 5	2.17%	0.60%	0.08%
Sky 6	2.03%	0.52%	0.11%
Sky 7	2.14%	0.59%	0.05%
Sky 8	1.93%	0.54%	0.03%
Sky 9	2.30%	0.68%	0.05%
Sky 10	1.73%	0.47%	0.02%
AVERAGE	2.10%	0.59%	0.06%

LIBP – large network

- Starting COOJA with "ant run" will give you the default Java maximum memory
  - 5 – 10 emulated nodes
- If you use "ant run_bigmem" you will be able to simulate/emulate larger networks.

LIBP – large network




PowerTracker: 50 motes

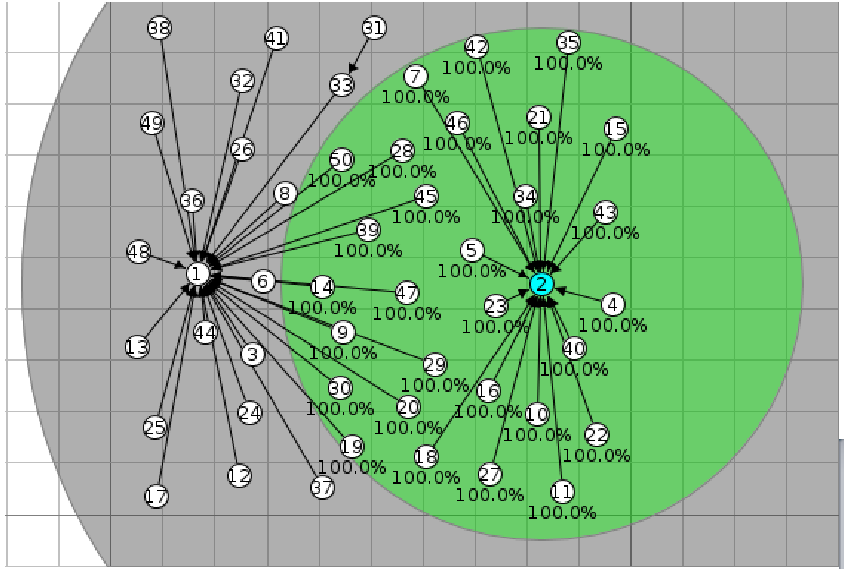
Mote	Radio on (%)	Radio TX (%)	Radio RX (%)
Contiki 1	100.00%	0.21%	0.37%
Contiki 2	100.00%	0.01%	0.22%
Contiki 3	100.00%	0.01%	0.38%
Contiki 4	100.00%	0.01%	0.17%
Contiki 5	100.00%	0.03%	0.57%
Contiki 6	100.00%	0.01%	0.47%
Contiki 7	100.00%	0.01%	0.19%
Contiki 8	100.00%	0.01%	0.28%
Contiki 9	100.00%	0.01%	0.20%
Contiki 10	100.00%	0.01%	0.28%
Contiki 11	100.00%	0.01%	0.20%
Contiki 12	100.00%	0.01%	0.38%
Contiki 13	100.00%	0.01%	0.53%
Contiki 14	100.00%	0.01%	0.33%
Contiki 15	100.00%	0.01%	0.43%
Contiki 16	100.00%	0.01%	0.14%
Contiki 17	100.00%	0.01%	0.52%
Contiki 18	100.00%	0.04%	0.48%
Contiki 19	100.00%	0.01%	0.36%
Contiki 20	100.00%	0.01%	0.40%

Compiled **50 Cooja Motes**

(Simulated motes – run as native java code)

Downside: Cannot do any power profiling

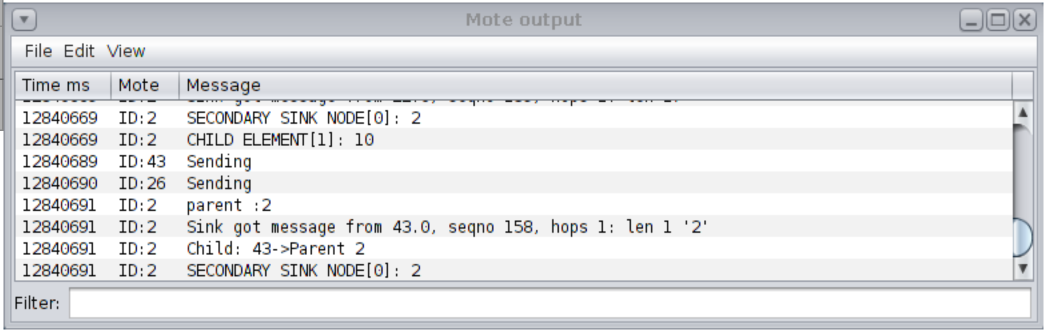
LIBP – 2 sinks



Node ID 1 : Primary Sink

Node ID 2 : Secondary Sink

Load balanced network with 2 sink nodes

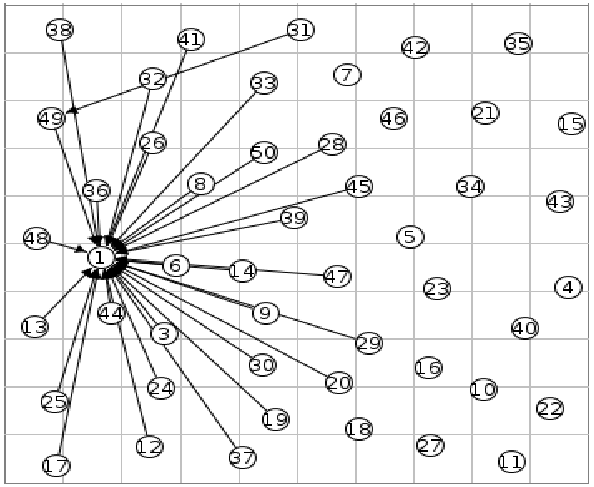


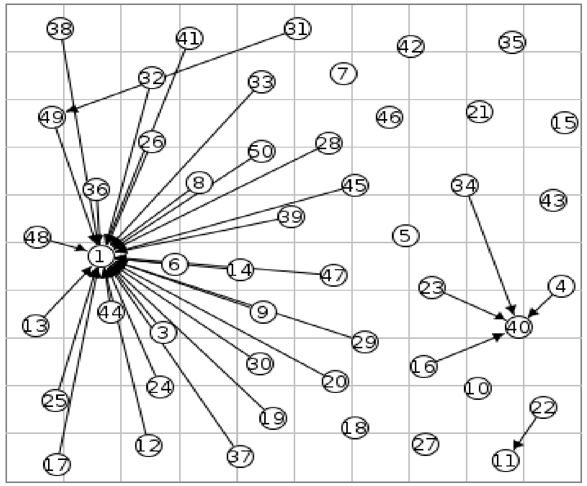
```
Time ms    Mote   Message
12840669   ID:2   SECONDARY SINK NODE[0]: 2
12840669   ID:2   CHILD ELEMENT[1]: 10
12840689   ID:43  Sending
12840690   ID:26  Sending
12840691   ID:2   parent :2
12840691   ID:2   Sink got message from 43.0, seqno 158, hops 1: len 1 '2'
12840691   ID:2   Child: 43->Parent 2
12840691   ID:2   SECONDARY SINK NODE[0]: 2
```

Filter:

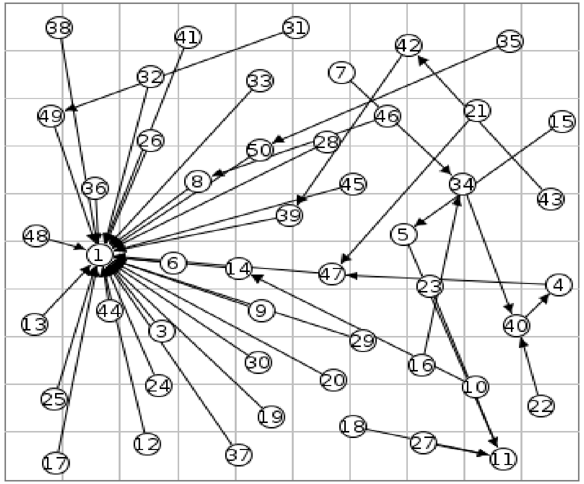
LIBP – 2 sinks

- The 2 sink nodes help with load balancing and network recovery
  - e.g. when one node goes offline, it's children (orphaned nodes) attempt to connect to the other sink

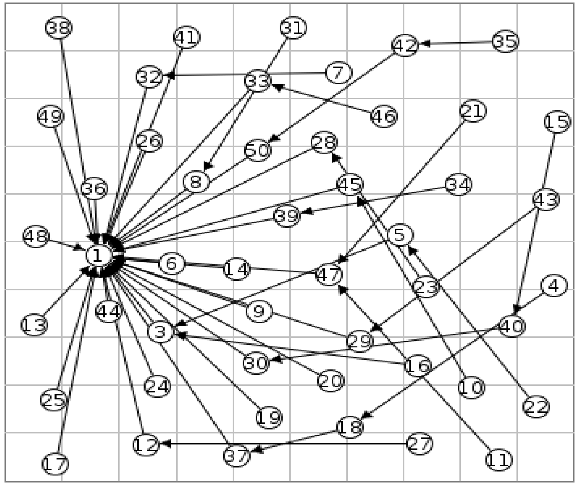

Secondary sink - offline


Recovery in process

LIBP – 2 sinks



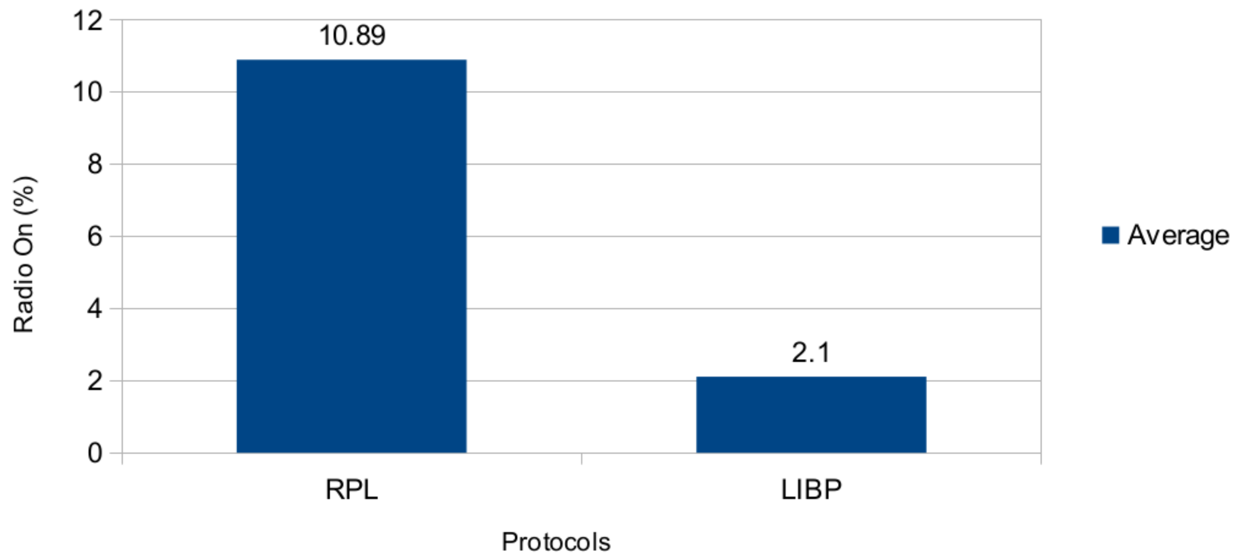
Orphaned nodes also attempt to connect with each other



Network has recovered and every node is making use of Node 1 as its sink node

Recovery in process

Comparison of RPL and LIBP Radio On Averages



LIBP uses less power amongst **10 Skymotes** in relation to keeping their radios on, thus creating a more energy efficient network.

References

[1] Alan, A., & Pritsker, B. (n.d.). Why Simulation Works. *Proceedings of the 1989 Winter Simulation Conference*. Retrieved from http://www.sfu.ca/~vdabbagh/p1-pritsker.pdf

[2] Voigt, T. *Contiki COOJA Crash Course*. Swedish Institute of Computer Science. Retrieved from https://www.sics.se/~thiemo/seniot09cccc-slides.pdf

[3] Kopf, D. *What is Difference Between The Energest and PowerTrace*. Retrieved from http://contiki-developers.narkive.com/VMpBTquh/what-is-difference-between-the-energest-and-powertrace

[4] Bagula, A., Djenouri, D., Karbab, E. *Ubiquitous Sensor Network Management: The Least Interference Beaconing Model*. In Proceedings of PIMRC 2013, Pages 2352-2356, 2013.

[5] Lutando Ngqakaza & Antoine Bagula, "**Least Path Interference Beaconing Protocol (LIBP): A Frugal Routing Protocol for The Internet-of-Things**", in proceedings of the IFIP Wired/Wireless Internet Communications WWIC 2014, Lecture Notes in Computer Science Volume 8458, 2014, pp 148-161, 2014.