Hands on Contiki OS and Cooja Simulator (Part I)

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Outline

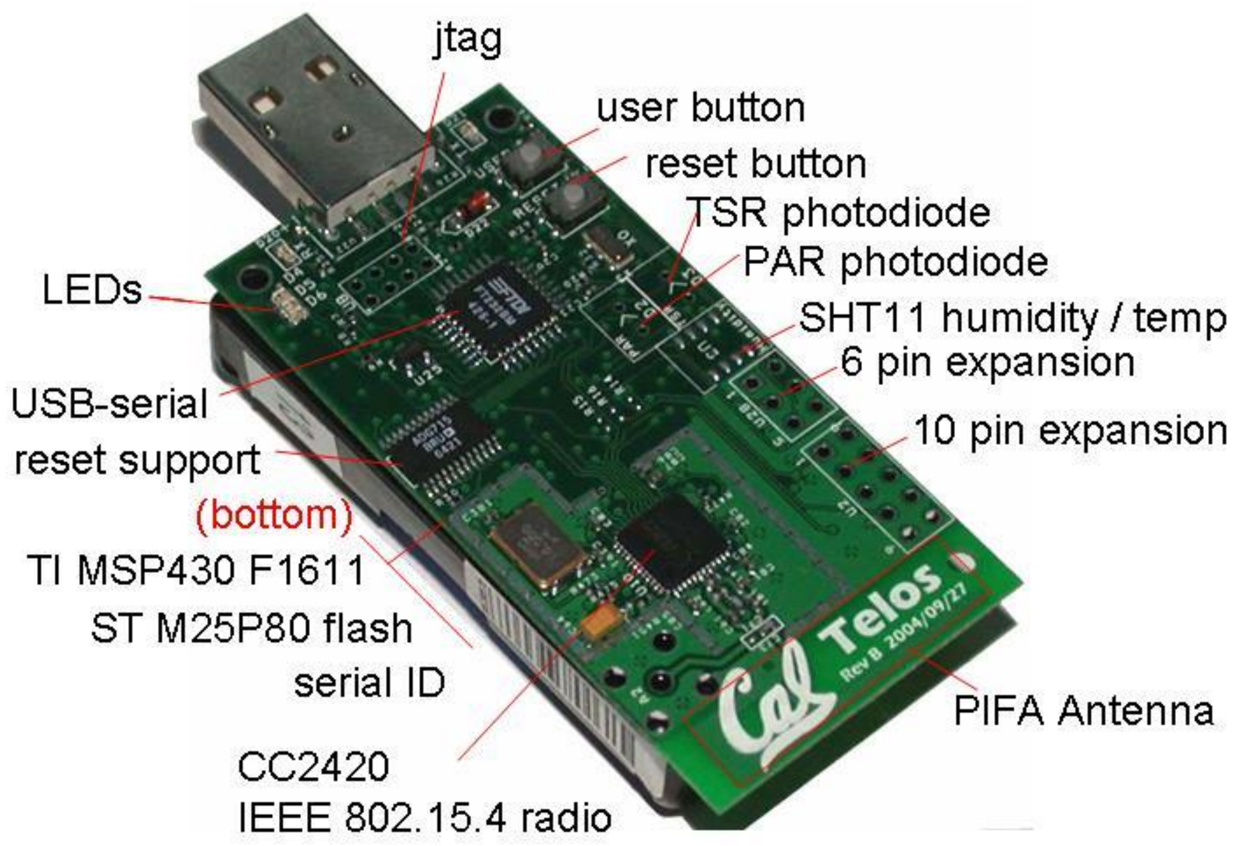
- Contiki Overview
- Basics
- Programming your first application
- The Cooja simulator
- IPv6 Networking

Goal of this Course

- Introduction to Contiki and the Cooja network simulator
  - Help you to start writing Contiki applications
  - Basis for further exploration
  - No low level details
  - Will not be able to cover everything on the slides
    - Together with the notes, you should be able to continue

Wireless Sensor Networks

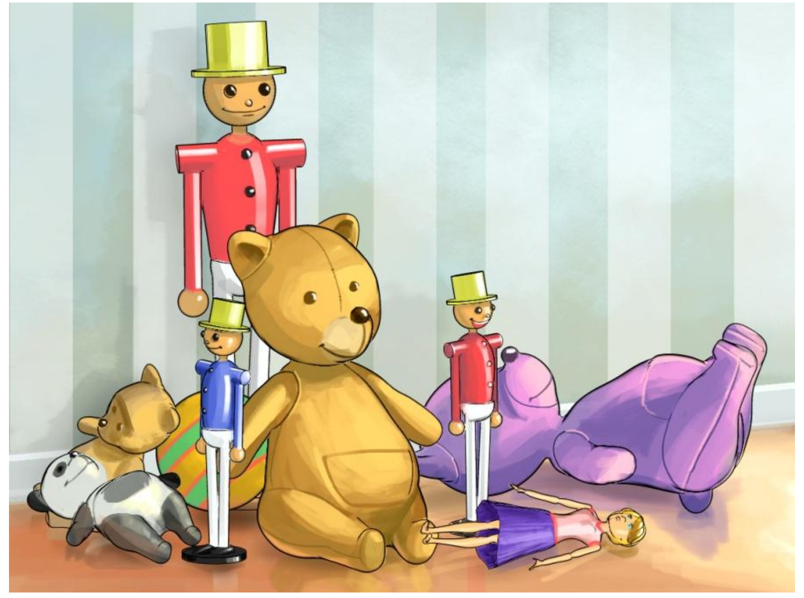
- Consist of many embedded units called sensor nodes, motes etc.
  - Sensors (and actuators)
  - Small microcontroller
  - Limited memory
  - Radio for wireless communication
  - Power source (often battery)



- Motes form networks and in a one hop or multi-hop fashion transport sensor data to base station

Applications

- Classic WSN applications
  - volcano monitoring
  - wildlife monitoring
  - tunnel monitoring and rescue
- …and many IoT-based applications
  - Smart Parking
  - Smart Lighting
  - Smart Plants
  - Smart Toys
  - Building/Home Automation



WSN Operating Systems

- OS is interface between hardware and programmer
  - Hides many details
- Contains drivers to radio and sensors, scheduling, network stacks, process & power management
- Due to memory constraints and target (embedded) not as convenient as OS for PCs
  - Limited user interaction
- TinyOS, Contiki, FreeRTOS, Mantis OS

Contiki Overview

- Contiki – a dynamic operating system for networked embedded systems
  - Main author and project leader: Adam Dunkels (Thingsquare, earlier SICS)
- Small memory footprint
  - Event-driven kernel, multiple threading models on top
- Designed for portability
  - Many platforms (Tmote Sky, Zolertia, RedBee etc.), several CPUs
  - Code hosted on github
- Used in both academia and industry
  - Contributors from Atmel, Cisco, Redwire LLC, SAP, SICS, Thingsquare, and others

Contiki Overview

Basically, Contiki is:

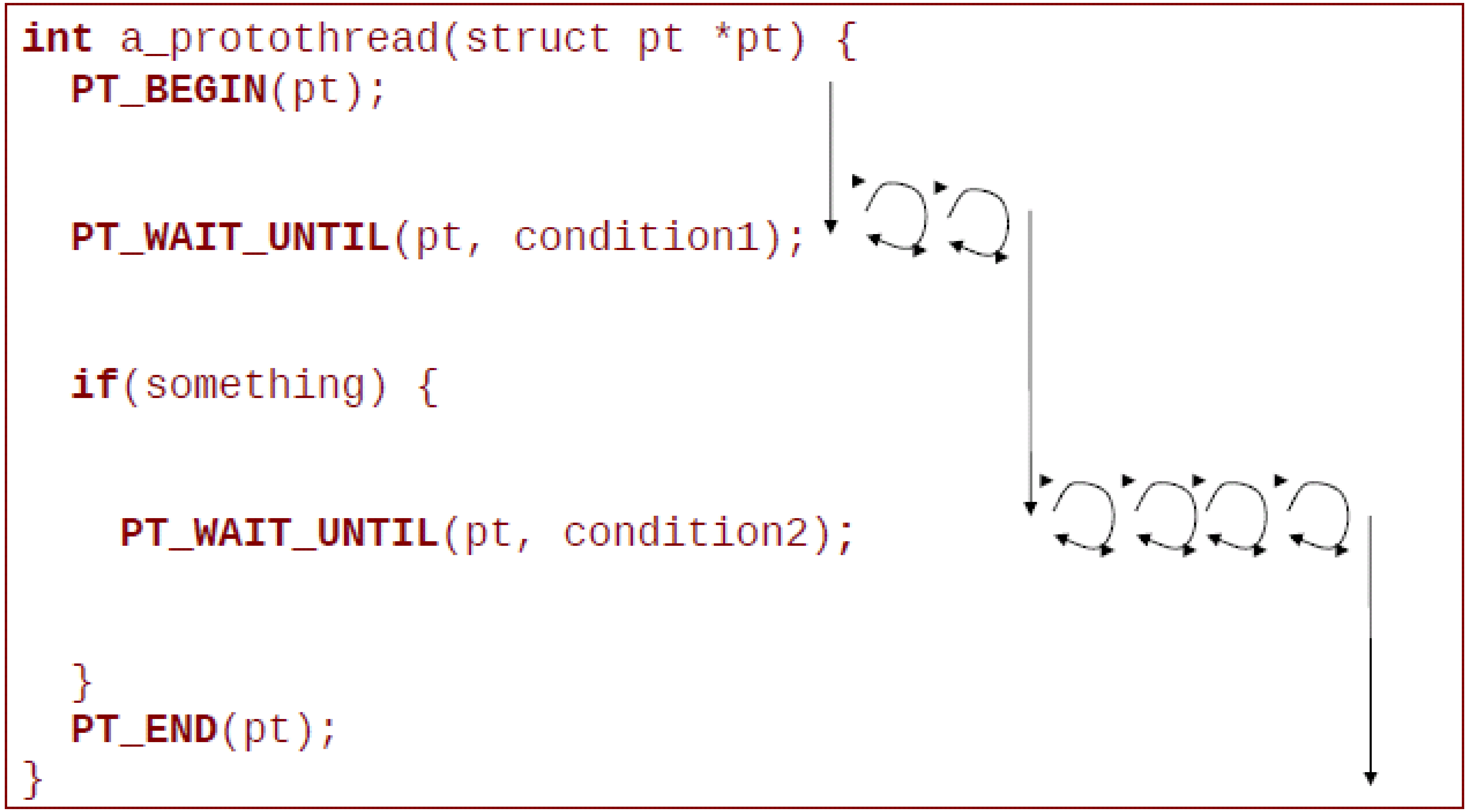
- A scheduler (event handler)
  - Loop that just takes the next event and processes it
  - Nothing to do->goes to sleep (MCU low power mode)
- Set of services
  - Networking, storage, timers, and others

Contiki Programming Model: Protothreads

- The Contiki kernel is event-based
  - invokes processes whenever something happens:
    - sensor events, processes starting, exiting

- **Protothreads** provide sequential flow of control on top of an event-based kernel
  - Easy to program
  - Also comes with some limitations, discussed later

Protothreads: Example

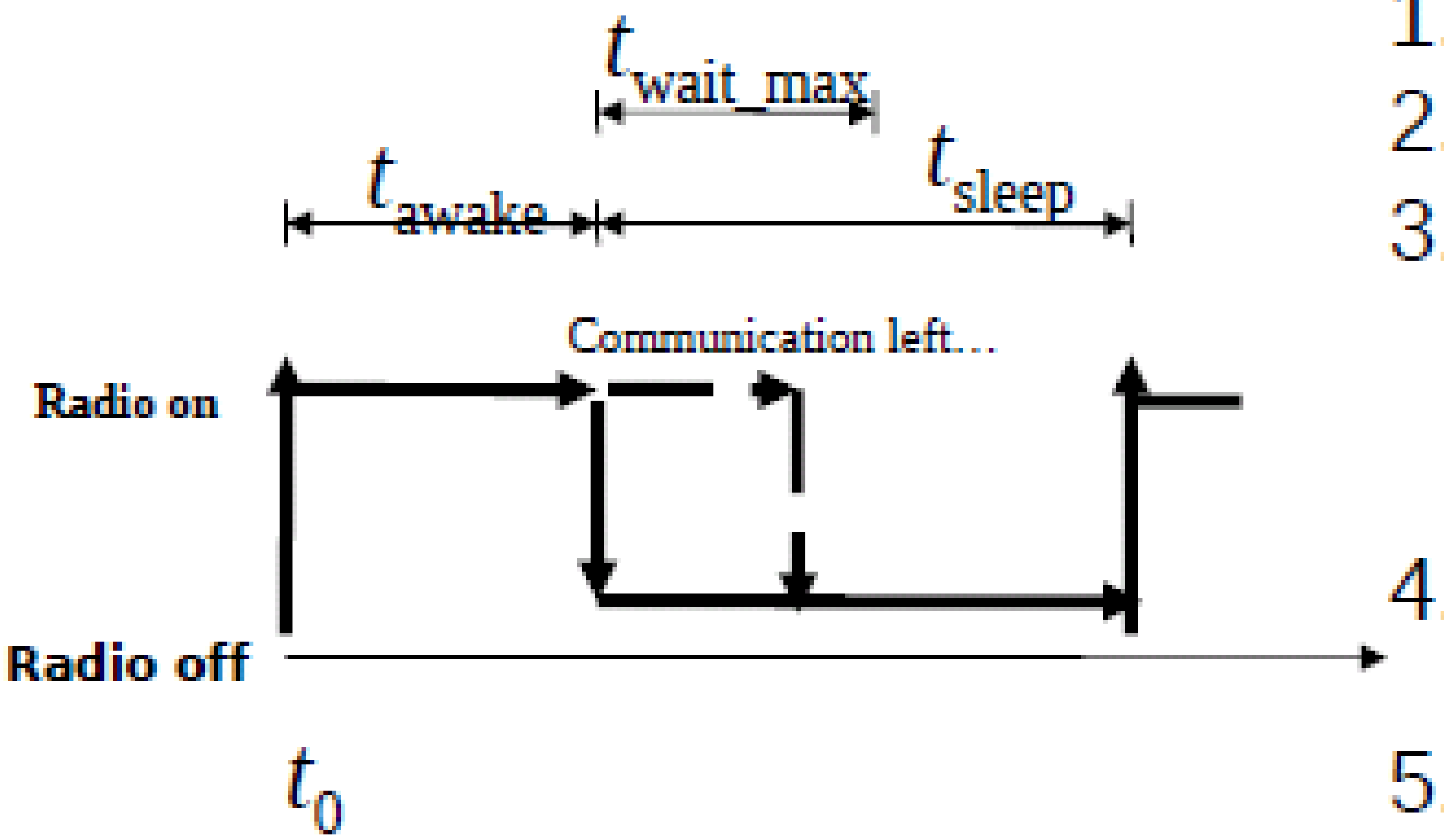


```
int a_protothread(struct pt *pt) {
  PT_BEGIN(pt);


  PT_WAIT_UNTIL(pt, condition1);


  if(something) {


    PT_WAIT_UNTIL(pt, condition2);


  }
  PT_END(pt);
}
```

Protothreads

- **Single** stack
  - Low memory usage, like events
- Sequential flow of control
  - No explicit state machines, just like threads
- Implemented using **local continuations** (a continuation is an abstract representation of the control state of a program)
  - When **Set**, capture the state of a function
  - When **resumed**, resume the state and perform a jump
  - Stack information across blocking calls must be manually stored and retrieved (e.g. static variable). See issue with protothreads next

Protothreads – Symplifying Event-driven Programming

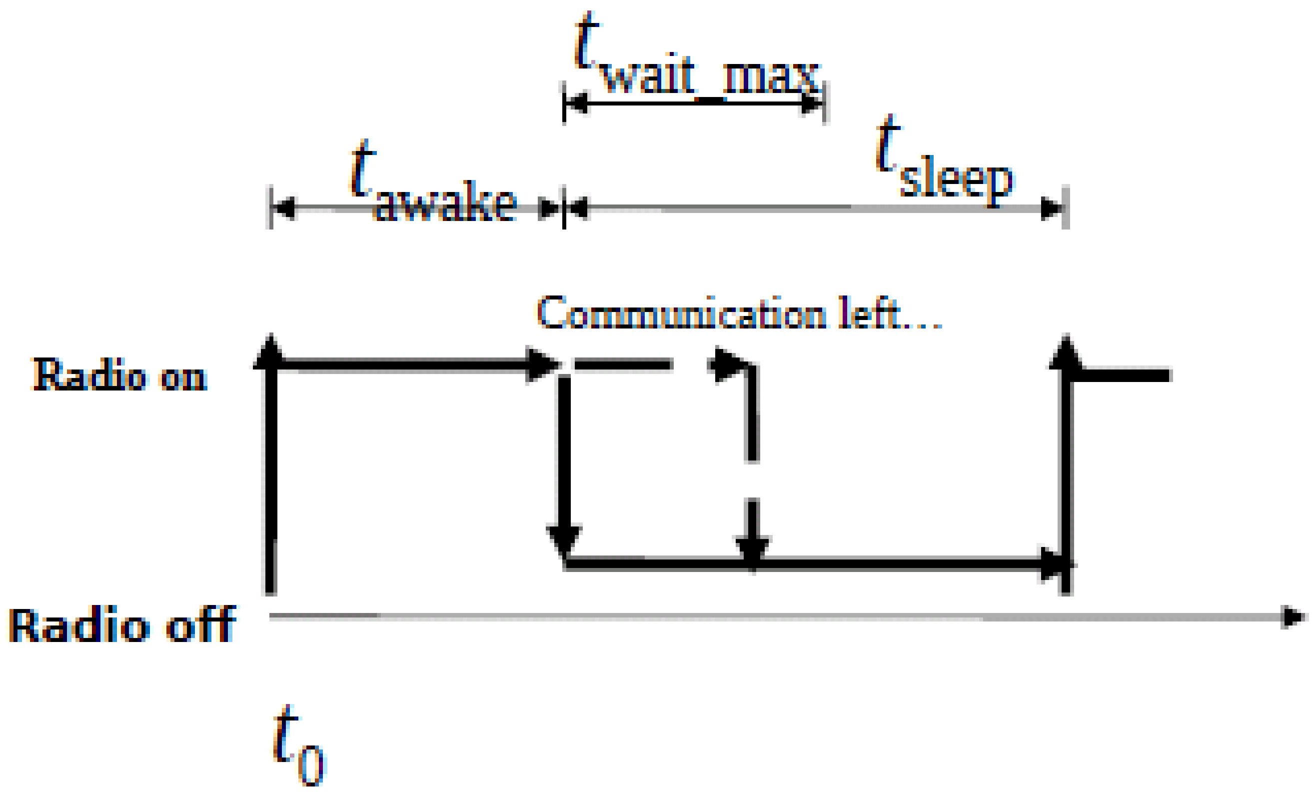


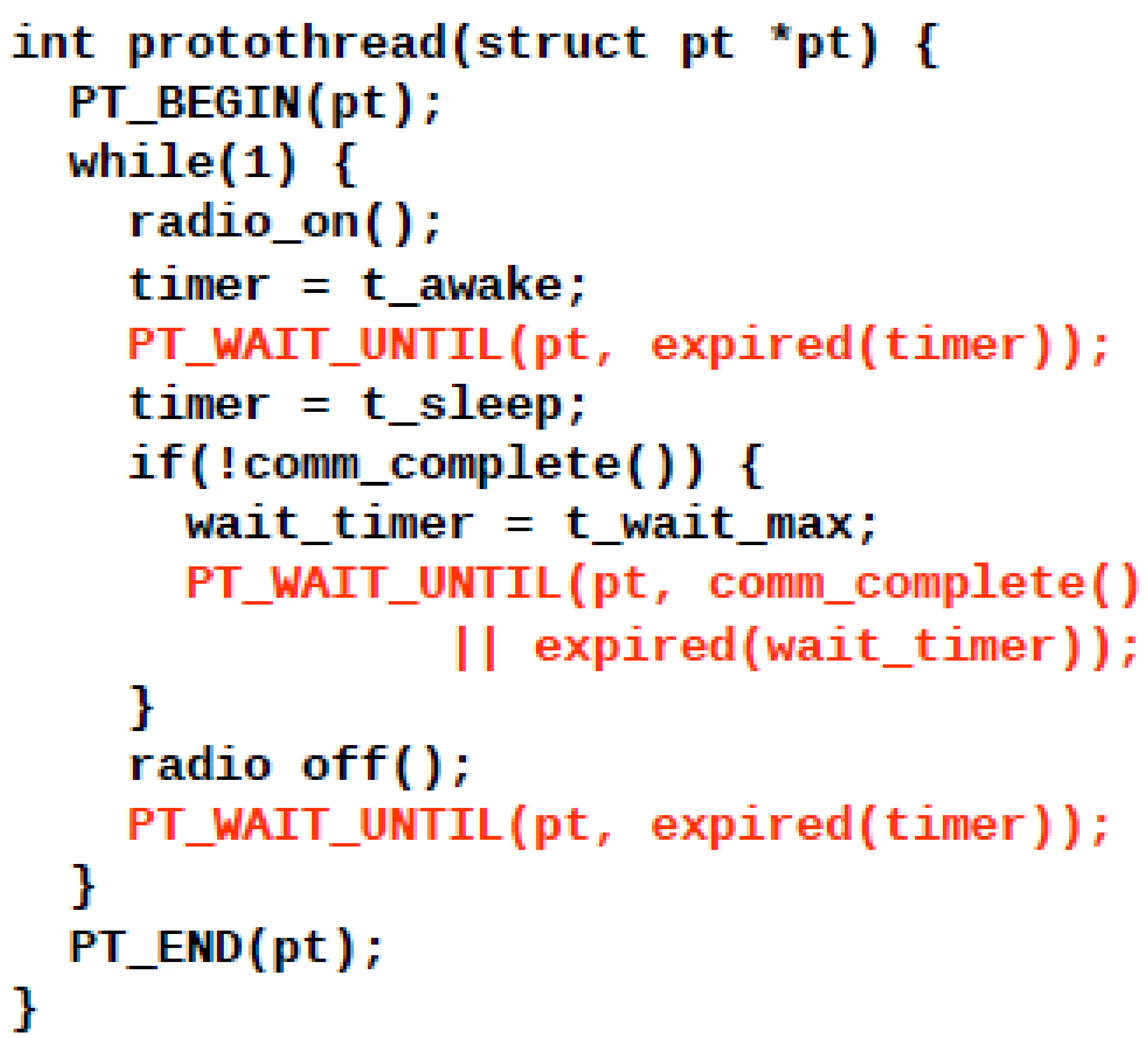
1. Turn radio on.
2. Wait until *t* = *t_0* + *t_awake*.
3. If communication has not completed, wait until it has completed or *t* = *t_0* + *t_awake* + *t_wait_max*.
4. Turn the radio off. Wait until *t* = *t_0* + *t_awake* + *t_sleep*.
5. Repeat from step 1.

No blocking wait!

Problem: with events, we cannot implement this as a five-step program!

Protothreads-based Implementation





```
int protothread(struct pt *pt) {
  PT_BEGIN(pt);
  while(1) {
    radio_on();
    timer = t_awake;
    PT_WAIT_UNTIL(pt, expired(timer));
    timer = t_sleep;
    if(!comm_complete()) {
      wait_timer = t_wait_max;
      PT_WAIT_UNTIL(pt, comm_complete()
               || expired(wait_timer));
    }
    radio off();
    PT_WAIT_UNTIL(pt, expired(timer));
  }
  PT_END(pt);
}
```

- Code uses structured programming (**if** and **while**), mechanisms evident from code

→ Protothreads make Contiki code **nice**

Contiki Processes

Contiki processes are protothreads:

- PROCESS_THREAD defines a new process
- PROCESS_BEGIN() and PROCESS_END()
- PROCESS_WAIT_EVENT() or PROCESS_YIELD() wait for new event to be posted to process
- PROCESS_WAIT_EVENT_UNTIL(condition c) waits for an event to be posted with extra condition, e.g.
  - Button has been pressed
  - Timer has expired

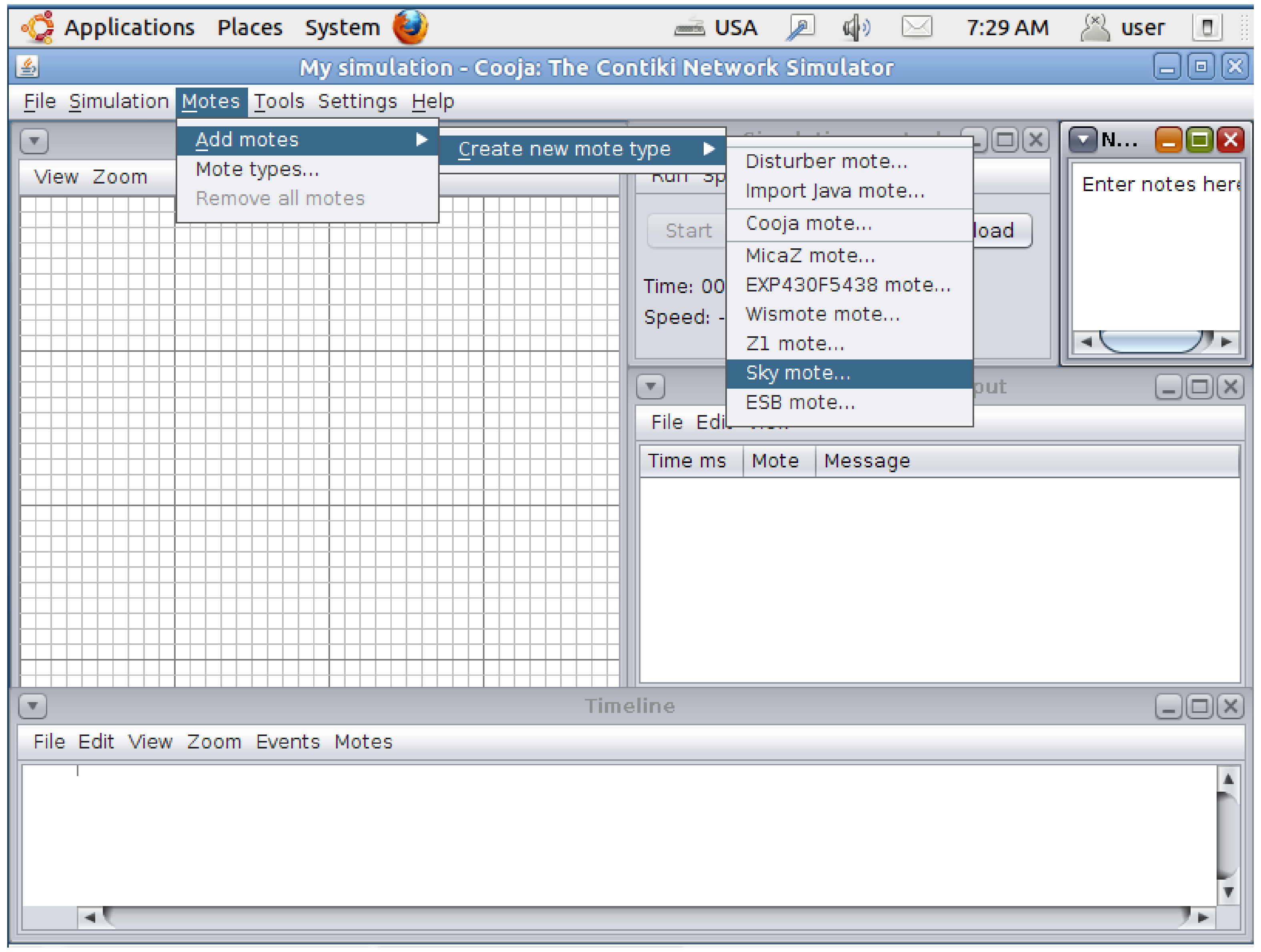
Protocol stacks

Protocol stacks in Contiki:

- uIP: world's smallest, fully compliant TCP/IP stack
  - Both IPv4 and IPv6, 6LowPAN, routing RPL, TCP/UPD support
  - Also higher layer protocols: HTTP, CoAP and many others
- Rime stack: protocol stack consisting of simple primitives
- MAC layers in Contiki:
  - Carrier Sense Multiple Access (CSMA)
  - NullMAC
- Radio Duty-Cycling (RDC) layers
  - ContikiMAC (default on Tmote Sky)
  - NullRDC (duty cycle off)
  - And others (less tested): LPP, X-MAC

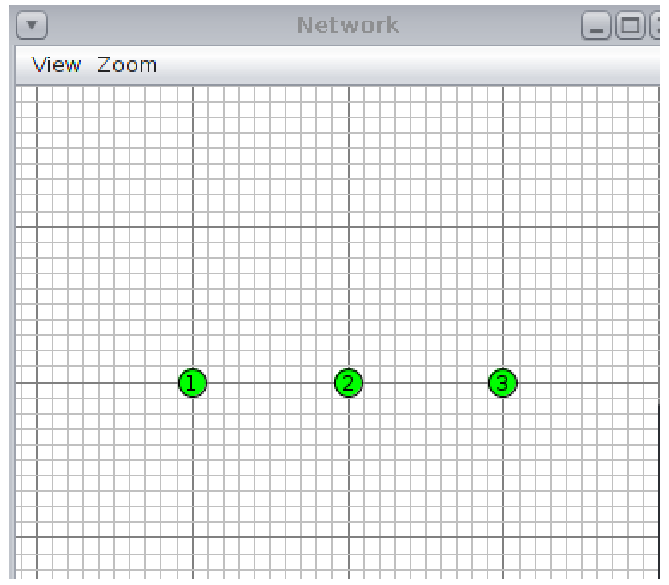
Cooja simulator

- COOJA: extensible Java-based network simulator for Contiki-based applications
  - Cross-level: Java nodes, Contiki nodes (deployable code), emulated nodes (deployable firmware, not necessarily contiki)
- MSPSim: sensor node emulator for MSP430-based nodes:
  - Tmote Sky, Zolertia Z1, Wismote, etc.
  - Enables cycle counting, debugging, power profiling etc.
  - Integrated into COOJA or standalone
- COOJA +MSPSim
- Simulate the network, emulate every nodes’ firmware
- Also enables interoperability testing for MSP-based platforms (e.g. IPv6 interop testing)

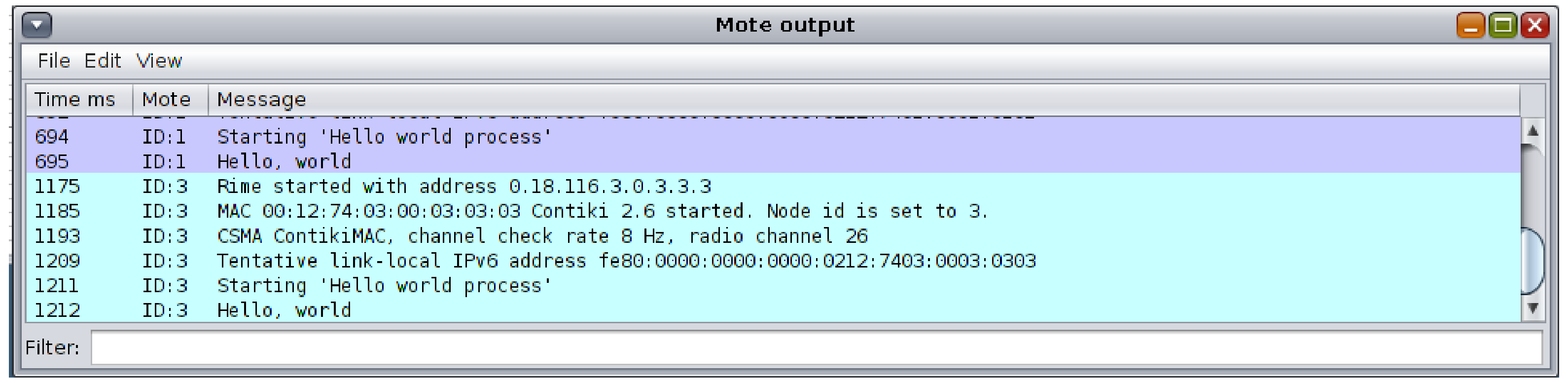


Cooja features

- Network Visualizer
  - mote type, grid, radio environment, radio traffic, etc.
  - Enables changes to the TX/INT range

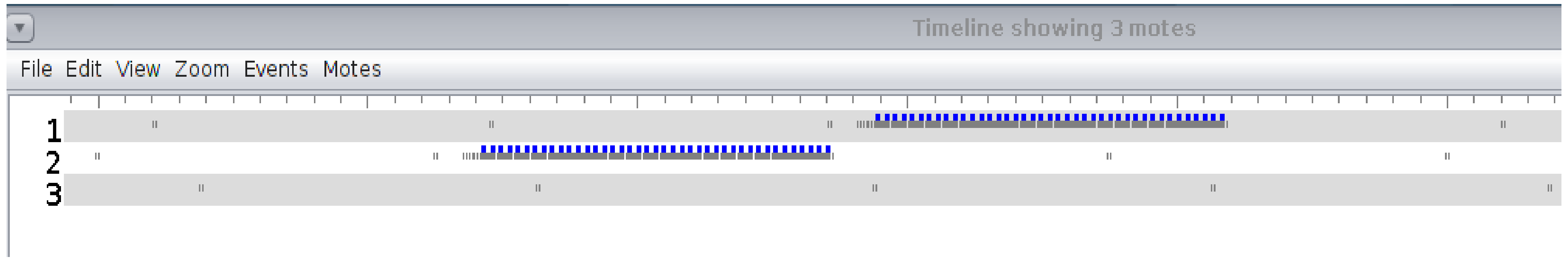


- Mote output
  - serial output of the nodes (e.g. *printf()*)

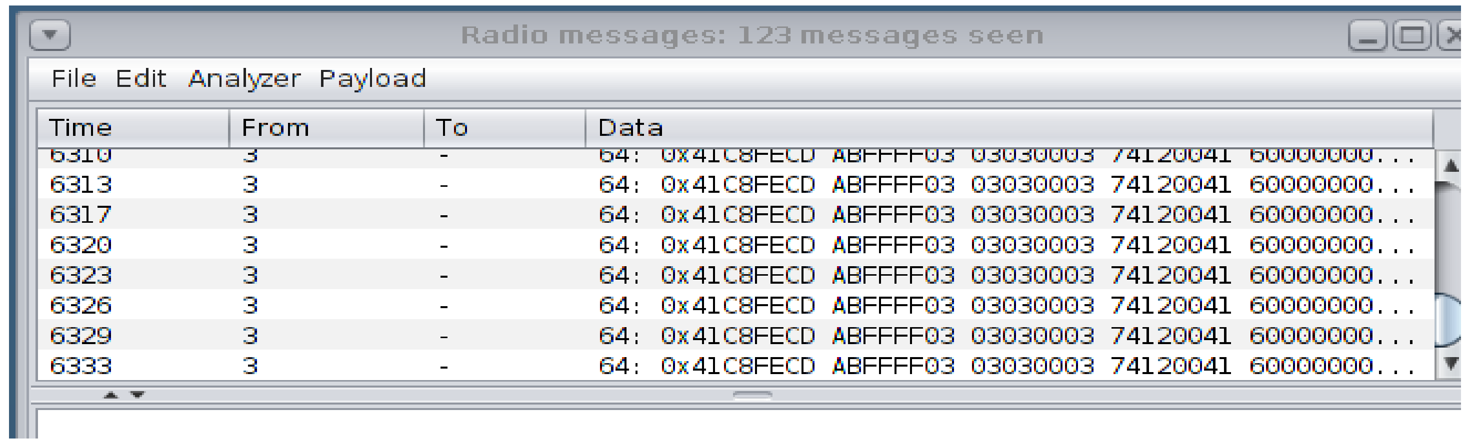


```
Time ms  Mote  Message
694      ID:1  Starting 'Hello world process'
695      ID:1  Hello, world
1175     ID:3  Rime started with address 0.18.116.3.0.3.3.3
1185     ID:3  MAC 00:12:74:03:00:03:03:03 Contiki 2.6 started. Node id is set to 3.
1193     ID:3  CSMA ContikiMAC, channel check rate 8 Hz, radio channel 26
1209     ID:3  Tentative link-local IPv6 address fe80:0000:0000:0000:0212:7403:0003:0303
1211     ID:3  Starting 'Hello world process'
1212     ID:3  Hello, world
```

- Timeline
  - radio activity of the nodes in real-time
  - E.g., radio status, ongoing packets



- Radio messages
  - capturing radio packets
  - Useful for Wireshark analysis



```
Time   From  To   Data
6310   3     -    64: 0x41C8FECD ABFFFF03 03030003 74120041 60000000...
6313   3     -    64: 0x41C8FECD ABFFFF03 03030003 74120041 60000000...
6317   3     -    64: 0x41C8FECD ABFFFF03 03030003 74120041 60000000...
6320   3     -    64: 0x41C8FECD ABFFFF03 03030003 74120041 60000000...
6323   3     -    64: 0x41C8FECD ABFFFF03 03030003 74120041 60000000...
6326   3     -    64: 0x41C8FECD ABFFFF03 03030003 74120041 60000000...
6329   3     -    64: 0x41C8FECD ABFFFF03 03030003 74120041 60000000...
6333   3     -    64: 0x41C8FECD ABFFFF03 03030003 74120041 60000000...
```

Programming your first app: Hello World

```
/* Declare the process */
PROCESS(hello_world_process, “Hello world”);
/* Make the process start when the module is loaded */
AUTOSTART_PROCESSES(&hello_world_process);

/* Define the process code */
PROCESS_THREAD(hello_world_process, ev, data) {
  PROCESS_BEGIN();            /* Must always come first */

  printf(“Hello, world!\n”);    /* code goes here *

  PROCESS_END();              /* Must always come last */
}
```

Makefile

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

UIP_CONF_IPV6=1

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

Running Hello World

- native platform (your VM)

  cd contiki/examples/hello-world

  make hello-world.native

  - After the compilation, start the program with

  ./hello-world.native

  - The program prints “Hello, World” and finishes (appears to hang). Interrupt it by pressing Ctrl-C

- Tmote sky platform
  - place Tmote in a USB and it will appear in the top of instant Contiki as “Future Technologies Device”. Click on name to connect it to Instant Contiki.

  cd contiki/examples/hello-world

  make TARGET=sky hello-world.upload

  - When the compilation is finished, the uploading procedure starts (LEDS blink like crazy).
  - You can see the output of the program by logging into the node

  make login TARGET=sky

  - Press the reboot button to see some output

Contiki directories

- contiki/core
  - System source code; includes (among others)
  - net: rime, MACs, IP etc;
  - sys: processes
- contiki/examples
  - Lots of nice examples, see /ipv6 for examples with uIP stack
- contiki/apps
  - System apps (telnet, shell, deluge), not your application code!
- contiki/platform
  - Platform-specific code:
    - platform/sky/contiki-sky-main.c
    - platform/sky/contiki-conf.h
- contiki/cpu
  - CPU-specific code: one subdirectory per CPU
- contiki/tools
  - e.g. cooja, start with “ant run”
  - tools/sky contains serialdump (start with “./serialdump-linux -b115200 /dev/ttyUSB0”) and other useful stuff

Timers in Contiki

- struct timer
  - Passive timer, only keeps track of its expiration time
- struct etimer
  - Active timer, sends an event when it expires
- struct ctimer
  - Active timer, calls a function when it expires
- struct rtimer
  - Real-time timer, calls a function at an exact time. Reserved for OS internals

Events and Processes

`PROCESS_WAIT_EVENT();`

Waits for an event to be posted to the process

`PROCESS_WAIT_EVENT_UNTIL(condition c);`

Waits for an event to be posted to the process, with an extra condition. Often used: wait until timer has expired

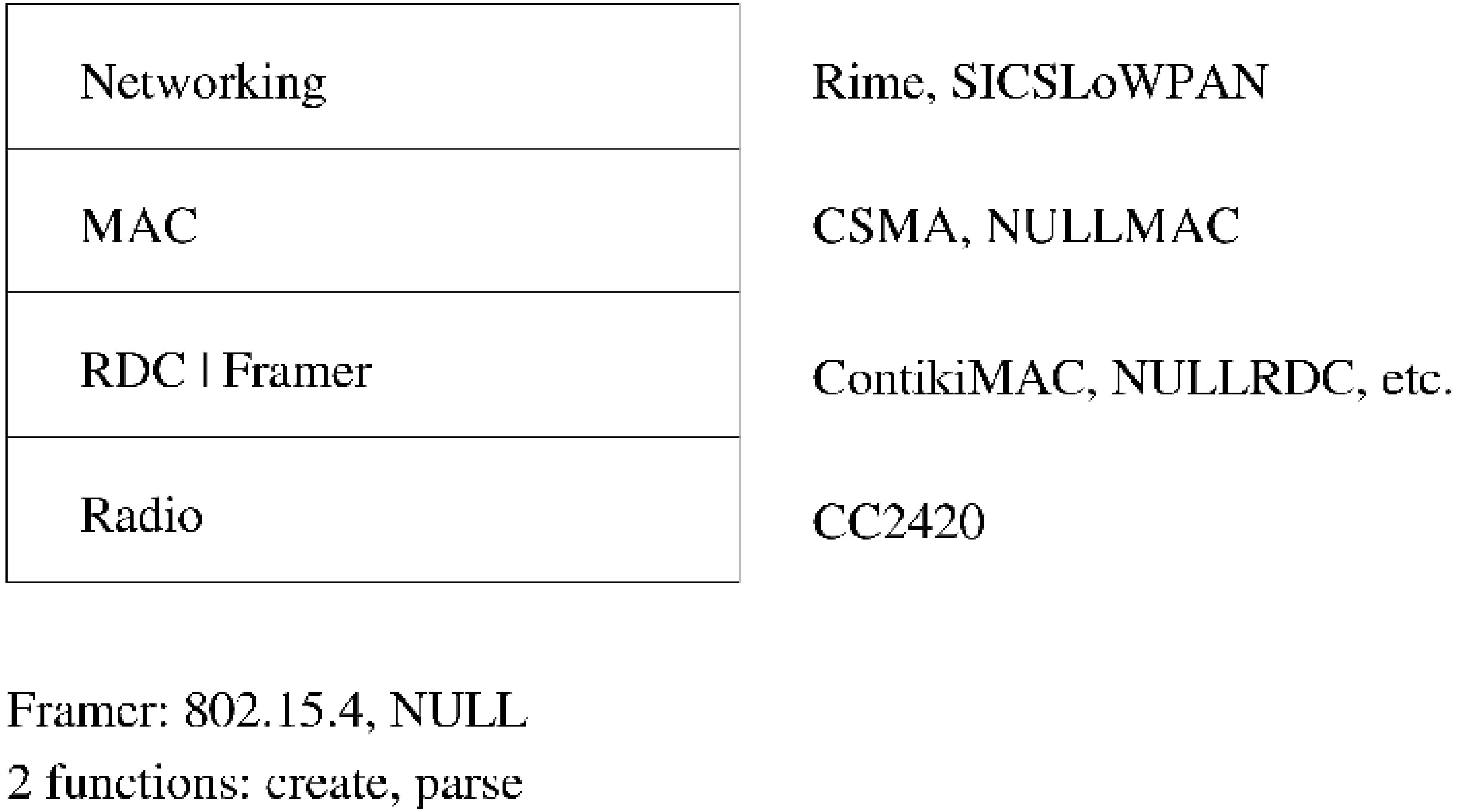
```
PROCESS_WAIT_EVENT_UNTIL(etimer_expired(&timer));
```

`PROCESS_POST(...)` and `PROCESS_POST_SYNCH(..)`

Post (a)synchronous event to a process.
The other process usually waits with `PROCESS_WAIT_EVENT_UNTIL(ev == EVENTNAME);`

Netstack

- By default, Contiki on Tmote sky uses ContikiMAC



Networking	Rime, SICSLoWPAN
MAC	CSMA, NULLMAC
RDC | Framer	ContikiMAC, NULLRDC, etc.
Radio	CC2420

Framer: 802.15.4, NULL
2 functions: create, parse

Measure Power Consumption with Energest

```
PROCESS_BEGIN();
  static struct etimer et;
  static unsigned long rx_start_time;
 ...
...
  rx_start_time = energest_type_time(ENERGEST_TYPE_LISTEN);
  lpm_start_time = energest_type_time(ENERGEST_TYPE_LPM);
  cpu_start_time = energest_type_time(ENERGEST_TYPE_CPU);
  tx_start_time = energest_type_time(ENERGEST_TYPE_TRANSMIT);
..
    printf("energy listen %lu tx %lu cpu %lu lpm %lu\n",
   energest_type_time(ENERGEST_TYPE_LISTEN) - rx_start_time,                    // in while loop
   energest_type_time(ENERGEST_TYPE_TRANSMIT) - tx_start_time,
   energest_type_time(ENERGEST_TYPE_CPU) - cpu_start_time,
   energest_type_time(ENERGEST_TYPE_LPM) - lpm_start_time);



  PROCESS_END();
}
```

Measure Power Consumption with Energest

- Now we have the times a component was on, eg
  - CPU on (“cpu”), CPU idle (“lpm”), Radio tx, Radio rx, Radio idle, Flash operations, etc
- Note: the cpu is always either on or idle, total runtime = “cpu” + “lpm”
- Can be used to estimate energy consumption
  - Based on power draw (from datasheet or measured)
  - Using other metrics, such as “duty cycle”, the portion of time with radio on
    - Duty cycle = (tx+rx) / (cpu+idle)

Measure Power Consumption with Energest

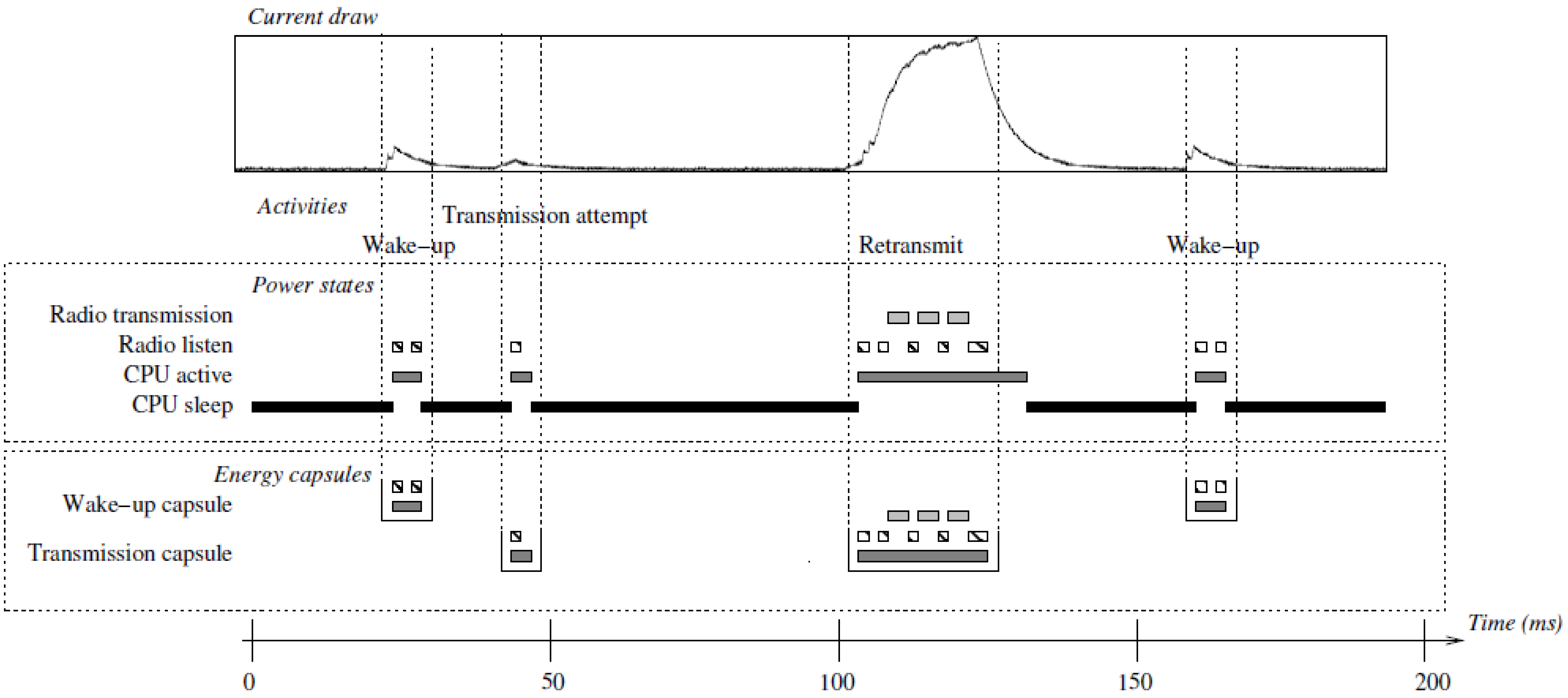


Figure 4: Measuring communication energy expenditure with Powertrace: the radio duty cycling layer maintains energy capsules for wake-ups, transmissions, and receptions. In the figure, capsules for wake-up and transmissions are shown. The transmission capsule is split across two activities: the first transmission attempt at 40 ms, which sensed another transmission in the ether and backed off, and the retransmission at 100 ms.

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Thank you