RIOT Hands-on Tutorial

Martine Lenders

Starting the RIOT

Preparations

For links go to `https://github.com/RIOT-OS/Tutorials`
Quick Setup (Using a Virtual Machine)

- Install and set up git
- Install VirtualBox & VirtualBox Extension Pack
- Install Vagrant
- `git clone --recursive https://github.com/RIOT-OS/Tutorials`
- Go to RIOT root directory: `cd Tutorials/RIOT`
- Run the Vagrant RIOT Setup
- Make sure you've run `vagrant ssh` and clone the Tutorials folder again, now in your virtual machine: `git clone --recursive https://github.com/RIOT-OS/Tutorials`

Recommended Setup (Without Using a VM)

- Install and set up git
- Install the build-essential packet (make, gcc etc.). This varies based on the operating system in use.
- Install Native dependencies
- Install OpenOCD
- Install GCC Arm Embedded Toolchain
- On OS X: install Tuntap for OS X
- additional tweaks necessary to work with the targeted hardware (ATSAMR21)
- Install `netcat` with IPv6 support (if necessary)
  `sudo apt-get install netcat-openbsd`
- `git clone --recursive https://github.com/RIOT-OS/Tutorials`
- Go to the Tutorials directory: `cd Tutorials`

Running RIOT

- Applications in RIOT consist at minimum of
  - a `Makefile`
  - a C-file, containing a `main()` function
- To see the code go to the task-01 directory:

```
cd task-01
ls
```

Your first application – The Makefile

```
# name of your application
APPLICATION = Task01

# If no BOARD is found in the environment, use this default:
BOARD ?= native

# This has to be the absolute path to the RIOT base directory:
RIOTBASE ?= $(CURDIR)/../../RIOT

# Comment this out to disable code in RIOT that does safety checking
# which is not needed in a production environment but helps in the
# development process:
CFLAGS += -DDEVELHELP

# Change this to 0 show compiler invocation lines by default:
QUIET ?= 1

# Modules to include:
USEMODULE += shell
USEMODULE += shell_commands
USEMODULE += ps

include $(RIOTBASE)/Makefile.include
```

Your first application – The C-file

```c
#include <stdio.h>
#include <string.h>

#include "shell.h"

int main(void)
{
    puts("This is Task-01");

    char line_buf[SHELL_DEFAULT_BUFSIZE];
    shell_run(NULL, line_buf, SHELL_DEFAULT_BUFSIZE);

    return 0;
}
```

Task 1.1: Run your first application as Linux process

1. Compile & run on `native`: `make all term`
2. Type `help`
3. Type `ps`
4. Modify your application:
   - Add a `printf("This application runs on %s", RIOT_BOARD);` *before* `shell_run()`
   - Recompile and restart `make all term`
   - Look at the result

Task 1.2: Run your first application on real hardware

1. Compile, flash and run on `samr21-xpro`
   `BOARD=samr21-xpro make all flash term`
   (or other `BOARD` if available)
2. Verify output of `RIOT_BOARD`

Custom shell commands

Writing a shell handler

- Shell command handlers in RIOT are functions with signature

```
int cmd_handler(int argc, char **argv);
```

- `argv`: array of strings of arguments to the command

```
print hello world   # argv == {"print", "hello", "world"}
```

- `argc`: length of `argv`

Adding a shell handler to the shell

- Shell commands need to be added manually to the shell on initialization

```
#include "shell.h"

static const shell_command_t shell_commands[] = {
    { "command name", "command description", cmd_handler },
    { NULL, NULL, NULL }
};

/* ... */
    shell_run(commands, line_buf, SHELL_DEFAULT_BUFSIZE)
/* ... */
```

Task 2.1 – A simple echo command handler

- Go to task-02 directory (`cd ../task-02`)
- Write a simple echo command handler in main.c:
  - First argument to the echo command handler shall be printed to output

```
> echo "Hello World"
Hello World
> echo foobar
foobar
```

Task 2.2 – Control the hardware

- `board.h` defines a macro `LED0_TOGGLE` to toggle the primary LED on the board.
- Write a command handler `toggle` in main.c that toggles the primary LED on the board

Multithreading

Threads in RIOT

- Threads in RIOT are functions with signature

```
void *thread_handler(void *arg);
```

- Use `thread_create()` from `thread.h` to start:

```
pid = thread_create(stack, sizeof(stack),
                    THREAD_PRIORITY_MAIN - 1,
                    THREAD_CREATE_STACKTEST,
                    thread_handler,
                    NULL, "thread");
```

RIOT kernel primer

Scheduler:

- Tick-less scheduling policy ($O(1)$):
  - Highest priority thread runs until finished or blocked
  - ISR can preempt any thread at all time
  - If all threads are blocked or finished:
    - Special IDLE thread is run
    - Goes into low-power mode

IPC (not important for the following task):

- Synchronous (default) and asynchronous (optional, by IPC queue initialization)

Task 3.1 – Start a thread

- Go to task-03 directory (`cd ../task-03`)
- Open `main.c`
- Reminder:

```
pid = thread_create(stack, sizeof(stack),
                    THREAD_PRIORITY_MAIN - 1,
                    THREAD_CREATE_STACKTEST,
                    thread_handler,
                    NULL, "thread");
```

- Start the thread `"thread"` from within `main()`
- Run the application on `native`: `make all term`
- Check your output, it should read: `I'm in "thread" now`

Timers

`xtimer` primer

- `xtimer` is the high level API of RIOT to multiplex hardware timers
- Examples for functionality:
  - `xtimer_now_usec()` to get current system time in microseconds
  - `xtimer_sleep(sec)` to sleep `sec` seconds
  - `xtimer_usleep(usec)` to sleep `usec` microseconds

Task 4.1 – Use `xtimer`

- Reminder: Functions `xtimer_now_usec()`, `xtimer_sleep()`, and `xtimer_usleep()` were introduced
- Go to task-04 directory (`cd ../task-04`)
- Note the inclusion of `xtimer` in Makefile

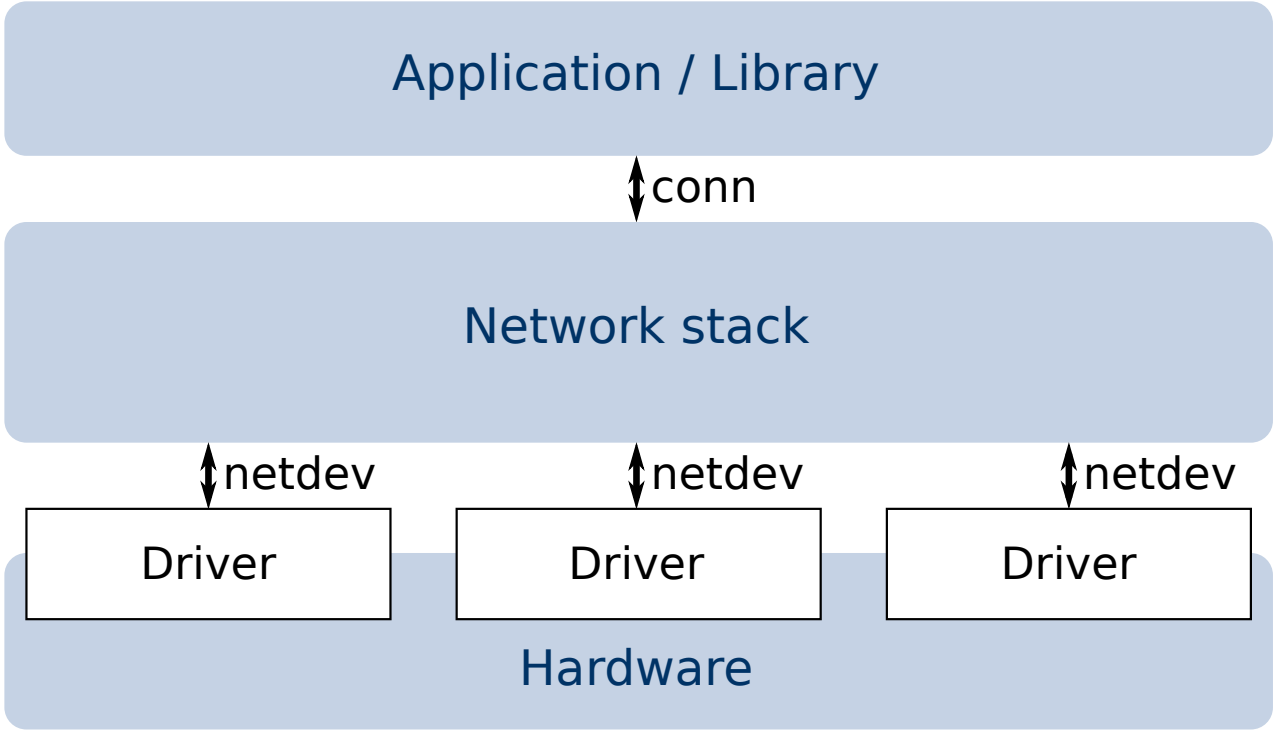
```
USEMODULE += xtimer
```

- Create a thread in `main.c` that prints the current system time every 2 seconds
- Check the existence of the thread with `ps` shell command

General networking architecture

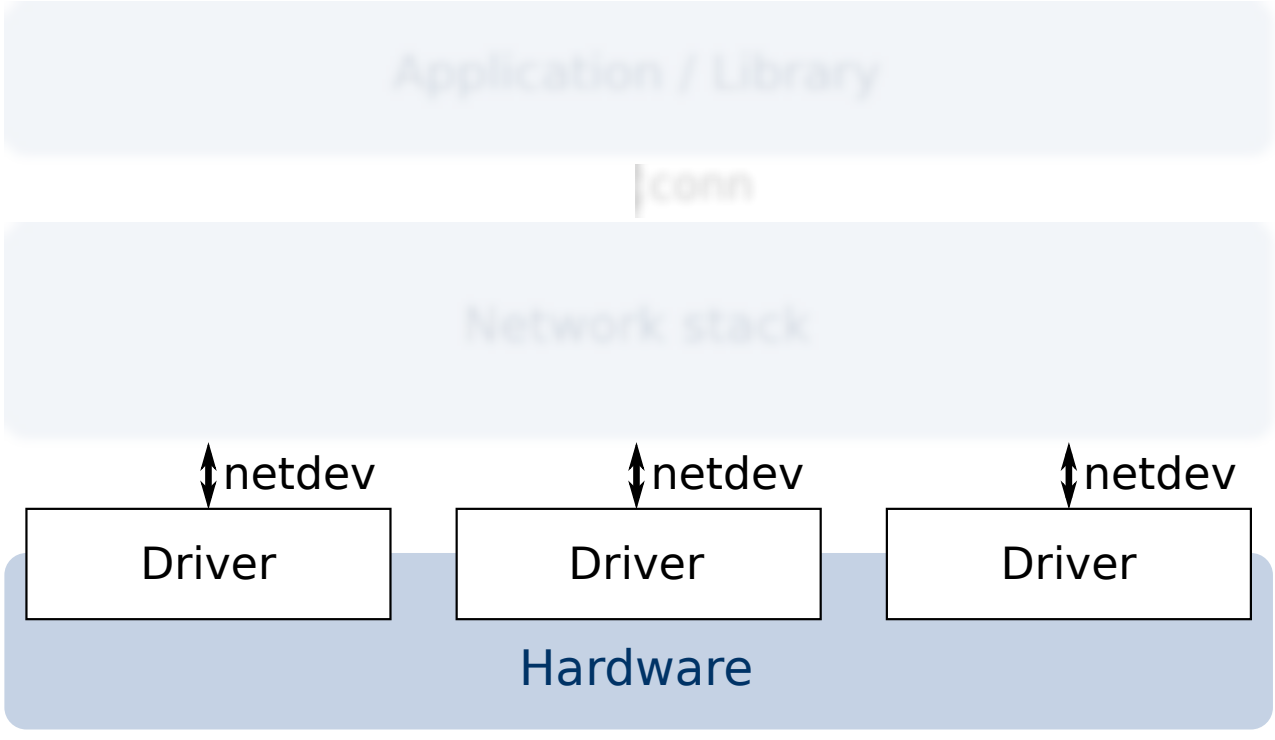
RIOT's Networking architecture

- Designed to integrate any network stack into RIOT



RIOT's Networking architecture

- Designed to integrate any network stack into RIOT



Including the network device driver

- Go to task-05 directory (`cd ../task-05`)
- Note inclusion of `netdev` modules in Makefile

```
USEMODULE += gnrc_netdev_default
USEMODULE += auto_init_gnrc_netif
```

Virtual network interface on `native`

- Use `tapsetup` script in RIOT repository:

```
./../RIOT/dist/tools/tapsetup/tapsetup -c 2
```

- Creates
  - Two TAP interfaces `tap0` and `tap1` and
  - A bridge between them (`tapbr0` on Linux, `bridge0` on OSX)
- Check with `ifconfig` or `ip link`!

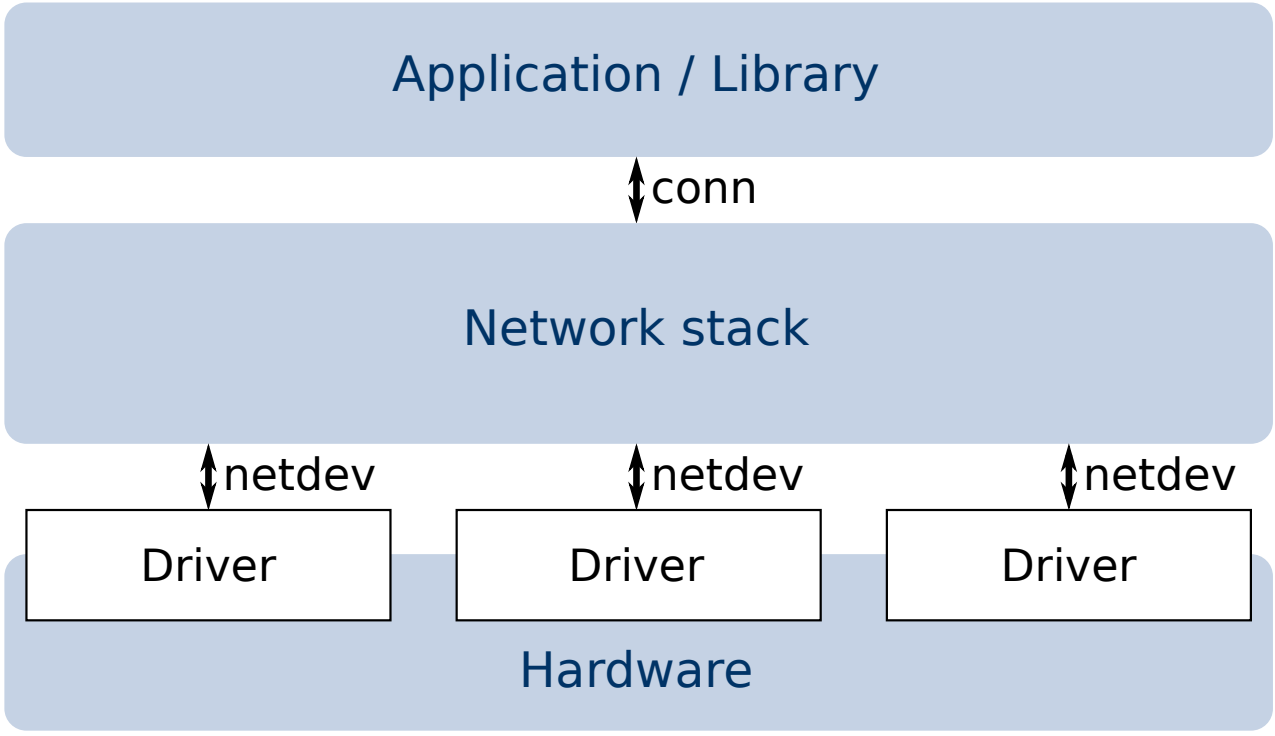
Task 5.1 – Your first networking application

- Run the application on `native`: `PORT=tap0 make all term`
- Type `help`
- Run a second instance with `PORT=tap1 make all term`
- Type `ifconfig` on both to get hardware address and interface number
- Use `txtsnd` command to exchange messages between the two instances

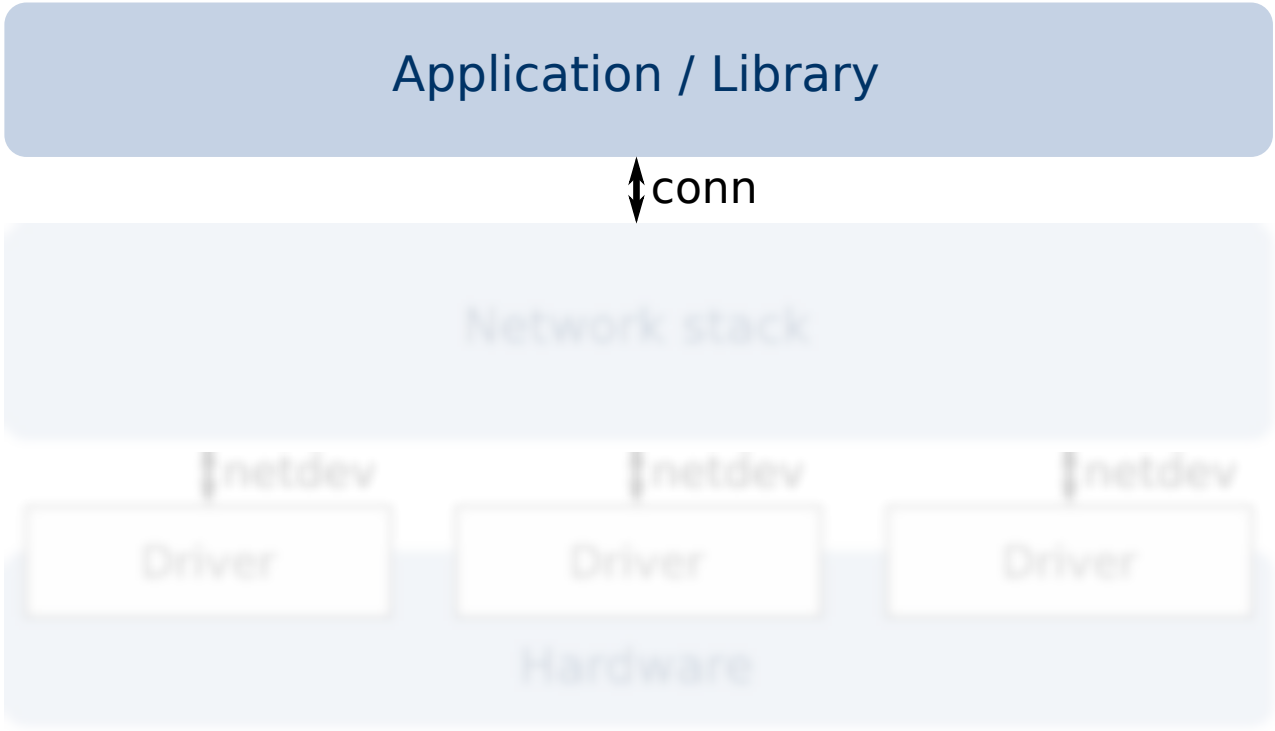
Task 5.2 – Use your application on real hardware

- Compile, flash, and run on the board `BOARD=samr21-xpro`
  `make all flash term`
- Type `ifconfig` to get your hardware addresses
- Use `txtsnd` to send one of your neighbors a friendly message

RIOT's Networking architecture



RIOT's Networking architecture



conn

- collection of unified connectivity APIs to the transport layer
- What's the problem with POSIX sockets?
  - too generic for most use-cases
  - numerical file descriptors (internal storage of state required)
  - in general: too complex for usage, too complex for porting
- protocol-specific APIs:
  - `conn_ip` (raw IP)
  - `conn_udp` (UDP)
  - `conn_tcp` (TCP)
  - ...
- both IPv4 and IPv6 supported

Task 6.1 – Use UDP for messaging

- Go to `task-06` directory `cd ../task-06`
- Note the addition of `gnrc_conn_udp` to Makefile
- `udp.c` utilizes `conn_udp_sendto()` and `conn_udp_recvfrom()` to exchange UDP packets
- Compile and run on two `native` instances
- Type `help`
- Use `udps 8888` to start a UDP server on port 8888 on first instance (check with `ps`)
- Use `ifconfig` to get link-local IPv6 address of first instance
- Send UDP packet from second instance using `udp` command to first instance

Task 6.2 – Communicate with Linux

- Compile and run a `native` instance
- Start a UDP server on port 8888 (using `udps`)
- Send a packet to RIOT from Linux using `netcat`

```
echo "hello" | nc -6u <RIOT-IPv6-addr>%tap0 8888
```

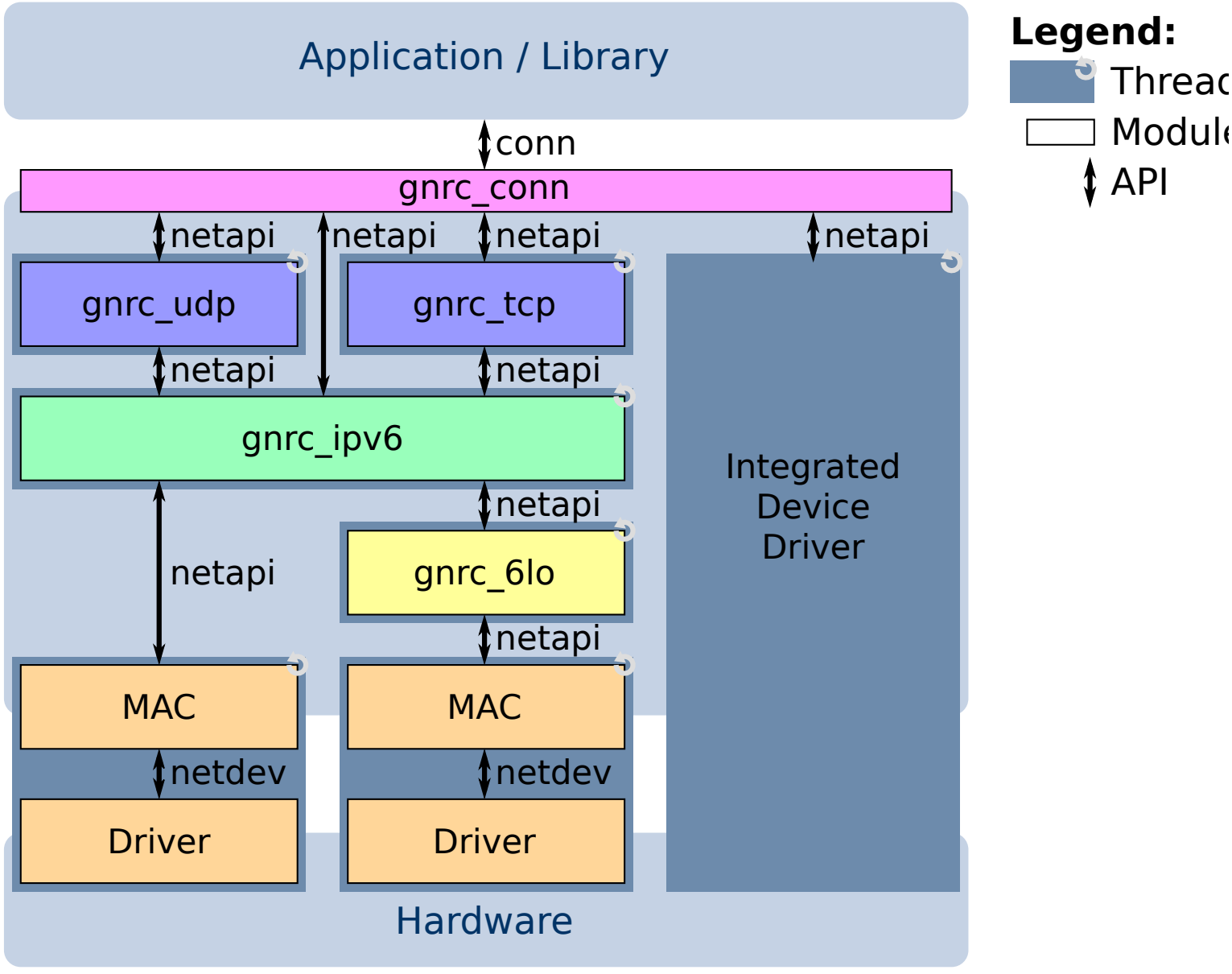
- Start a UDP server on Linux `nc -6lu 8888`
- Send a UDP packet from RIOT to Linux
  `udp <tap0-IPv6-addr> 8888 hello`

Task 6.3 – Exchange UDP packets with your neighbors

- Compile, flash and run on the board `BOARD=samr21-xpro make all flash term`
- Send and receive UDP messages to and from your neighbors using `udp` and `udps`

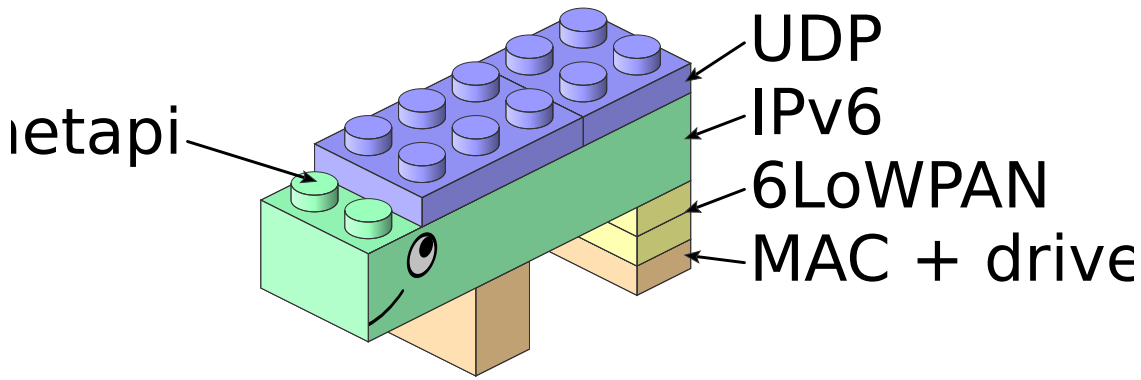
GNRC

The components of GNRC

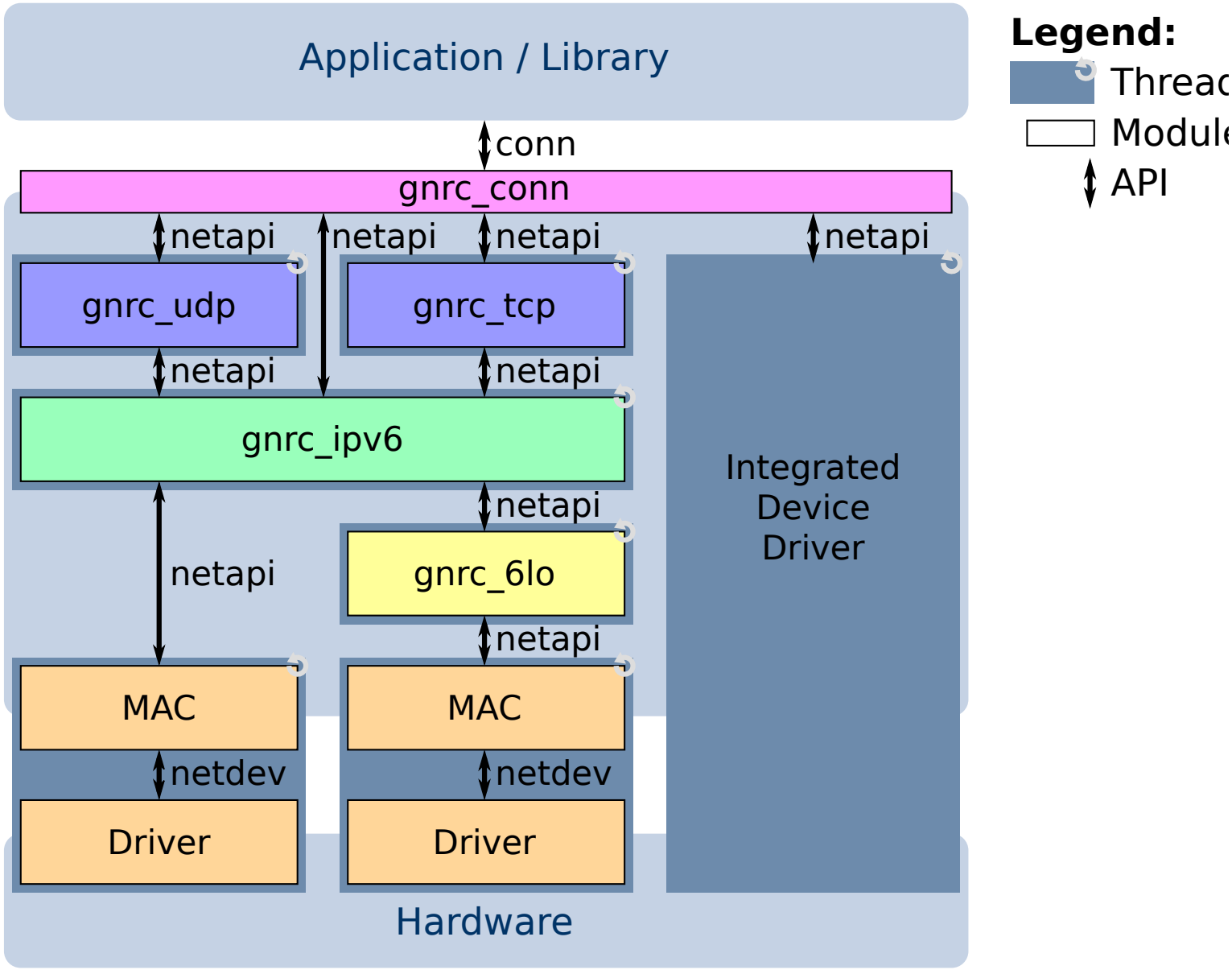


netapi

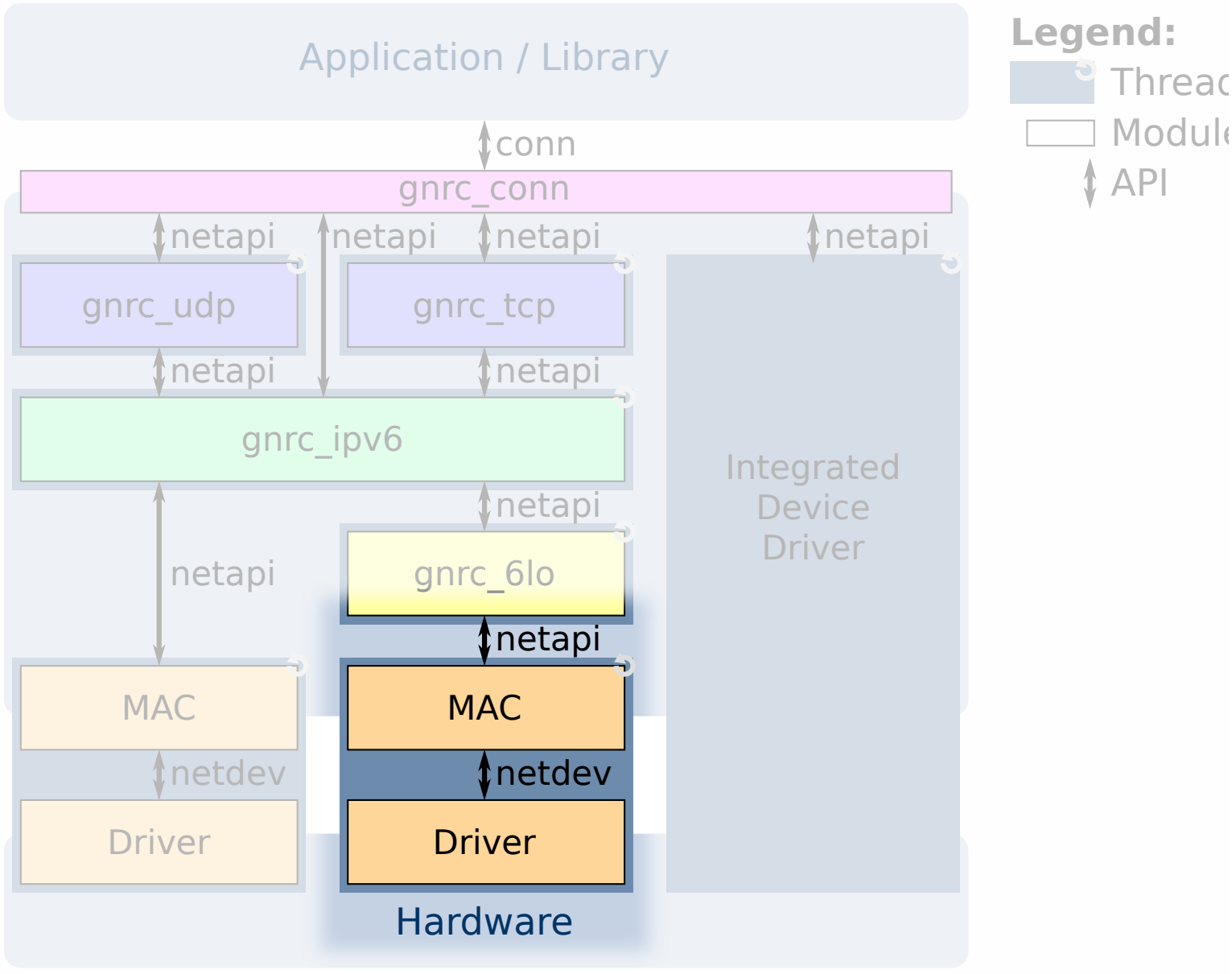
- Inter-modular API utilizing IPC
- Two asynchronous message types (don't expect reply) for data transfer:
  - `GNRC_NETAPI_MSG_TYPE_SND`: pass "down" the stack (send)
  - `GNRC_NETAPI_MSG_TYPE_RCV`: pass "up" the stack (receive)
- Two synchronous message types (expect reply) for option handling:
  - `GNRC_NETAPI_MSG_TYPE_GET`: get option value
  - `GNRC_NETAPI_MSG_TYPE_SET`: set option value
- Specification deliberately vague
  $\Rightarrow$ implementations can make own preconditions on data



Network interfaces in GNRC (1)

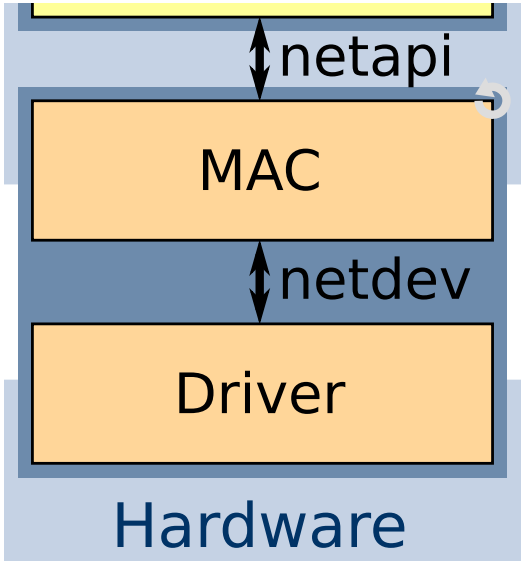


Network interfaces in GNRC (1)



Network interfaces in GNRC (2)

- `netapi`-capable thread as any other protocol implementation
- Implement MAC protocol
- Communication to driver via `netdev`
  $\Leftarrow$ timing requirements for e.g. TDMA-based MAC protocols



`netreg`

- How to know where to send `netapi` messages?

netreg

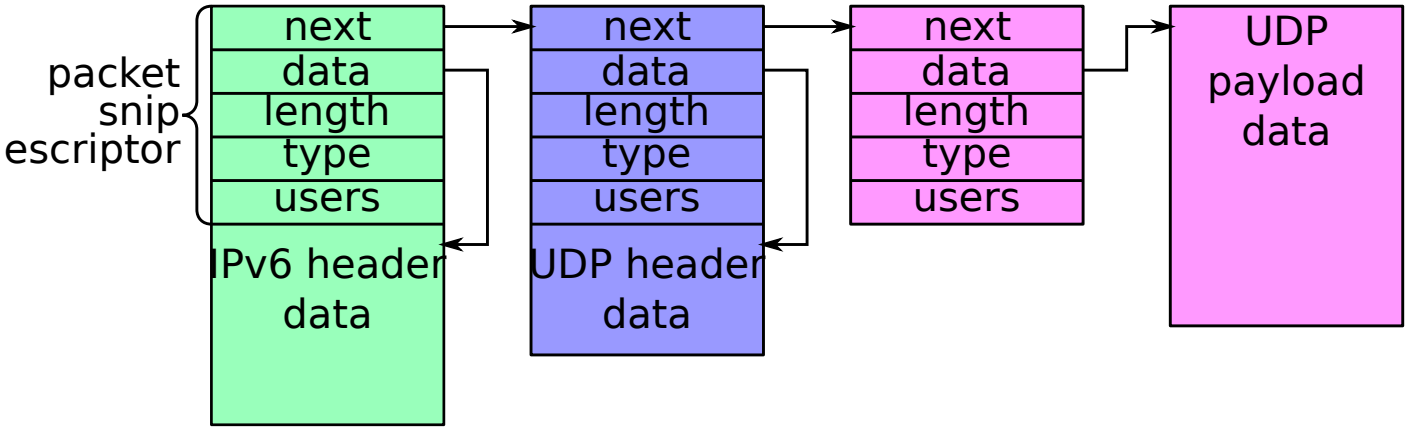
- How to know where to send `netapi` messages?
- Both protocol implementation and users can register to be interested in type + certain context (e.g. port in UDP)

```
gnrc_netreg_entry_t ipv6_handler = { NULL,
                                     GNRC_NETREG_DEMUX_CTX_ALL,
                                     ipv6_handler_pid};
gnrc_netreg_register(GNRC_NETTYPE_IPV6, &ipv6_handler);

gnrc_netreg_entry_t dns_handler = { NULL, PORT_DNS,
                                    dns_handler_pid};
gnrc_netreg_register(GNRC_NETTYPE_UDP, &dns_handler);
```

$\Rightarrow$ Find handler for packets in registry

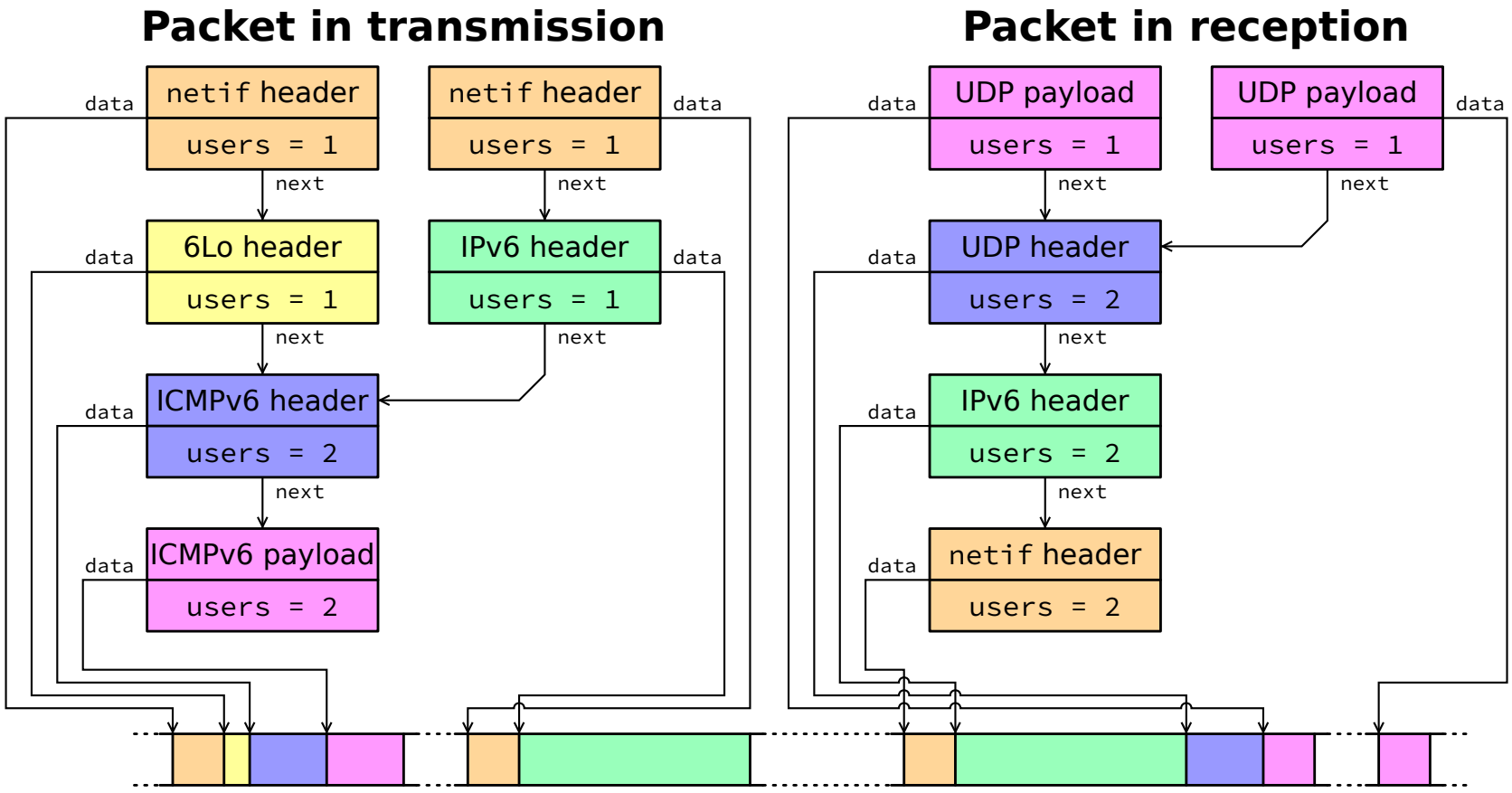
`pktbuf`

- Data packet stored in `pktbuf`
- Representation: list of variable-length "packet snips"
- Protocols can *mark* sections of data to create new snip
- Keeping track of referencing threads: reference counter `users`
  - If `users == 0`: packet removed from packet buffer
  - If `users > 1` and write access requested: packet duplicated (*copy-on-write*)



pktbuf – keeping duplication minimal

- Only copy up to most *current* packet snip
  ⇒ Packets become tree-like
  ⇒ Reverse order for received packets to only have one pointer



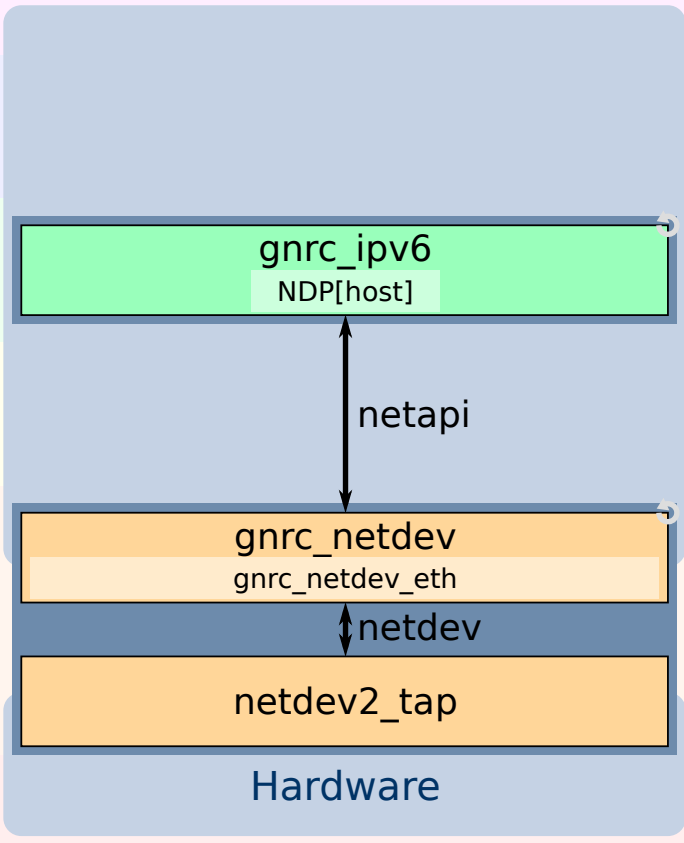
RIOT examples

The remaining slides utilize the RIOT examples:

```
cd ../RIOT/examples/
ls
```

gnrc_minimal example (native)

- * = name might be subject to change



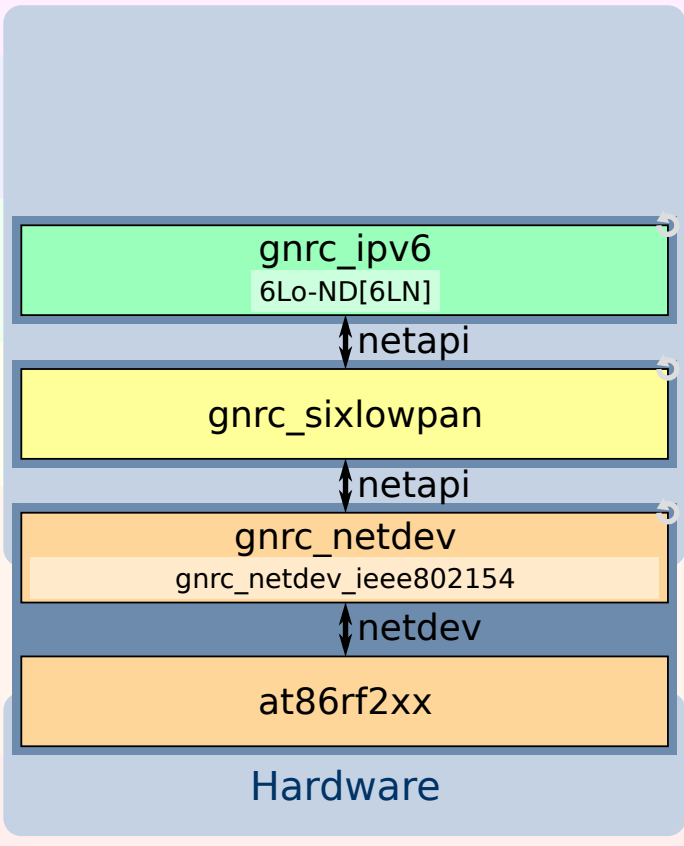

```
USEMODULE += gnrc_ipv6
USEMODULE += gnrc_ndp_host*
```

```
USEMODULE += auto_init_gnrc_netdev*
```

```
USEMODULE += gnrc_netdev_default*
```

gnrc_minimal example (samr21-xpro)

- * name might be subject to change




```
USEMODULE += gnrc_ipv6
USEMODULE += gnrc_sixlowpan_nd*
```

```
USEMODULE += gnrc_sixlowpan
USEMODULE += gnrc_sixlowpan_frag
USEMODULE += gnrc_sixlowpan_iphc
```

```
USEMODULE += auto_init_gnrc_netdev*
```

```
USEMODULE += gnrc_netdev_default*
```

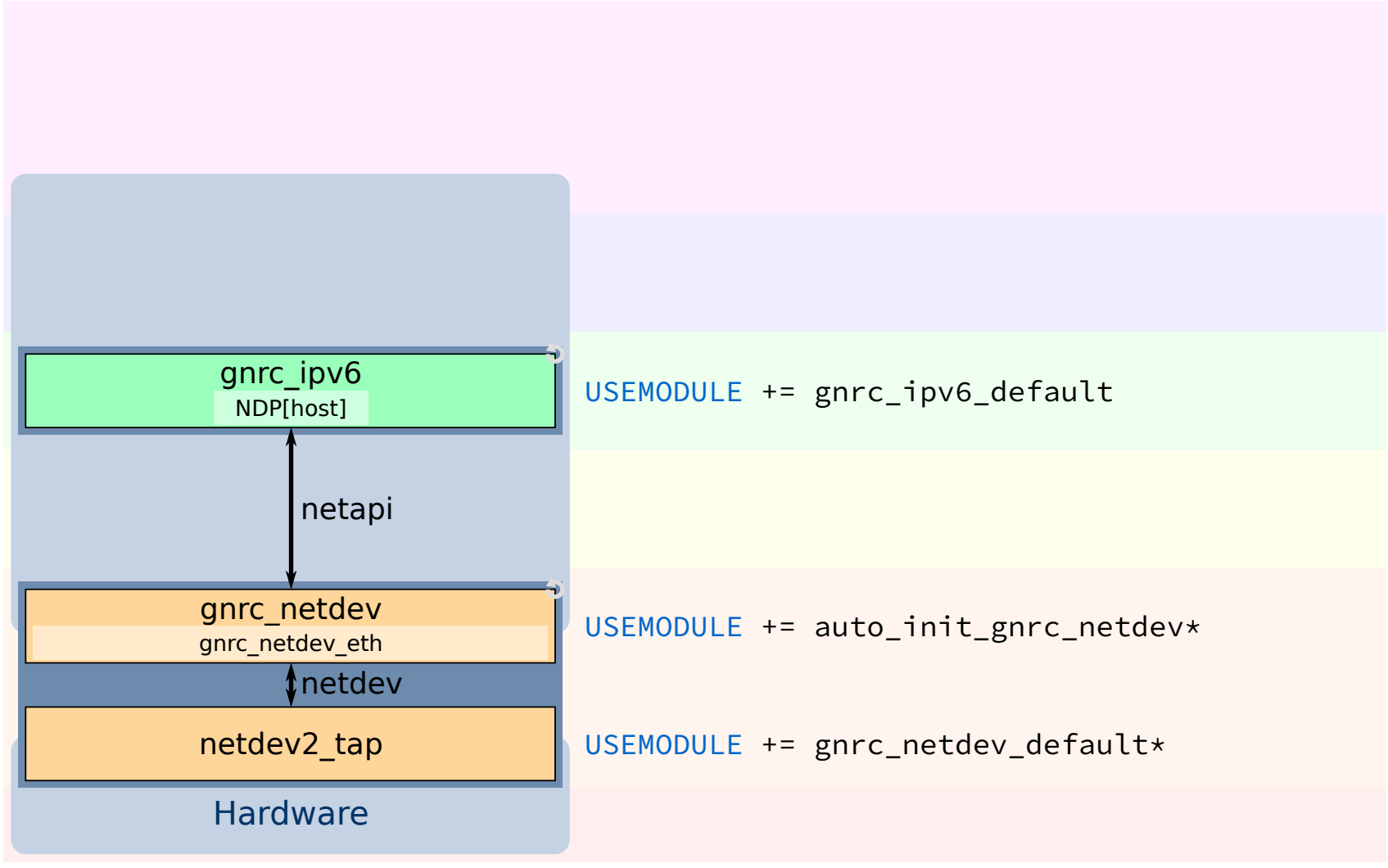
Some short-cuts (`Makefile.dep`)

Pseudo-module dependencies

- `gnrc_sixlowpan_default`:
  - `gnrc_sixlowpan`
  - `gnrc_sixlowpan_frag`
  - `gnrc_sixlowpan_iphc`
- `gnrc_ipv6_default`:
  - `gnrc_ipv6`
  - `gnrc_ndp_host` (if non-6Lo interface present)
  - `gnrc_sixlowpan_default` (if 6Lo interface present)
  - `gnrc_sixlowpan_nd` (if 6Lo interface present)

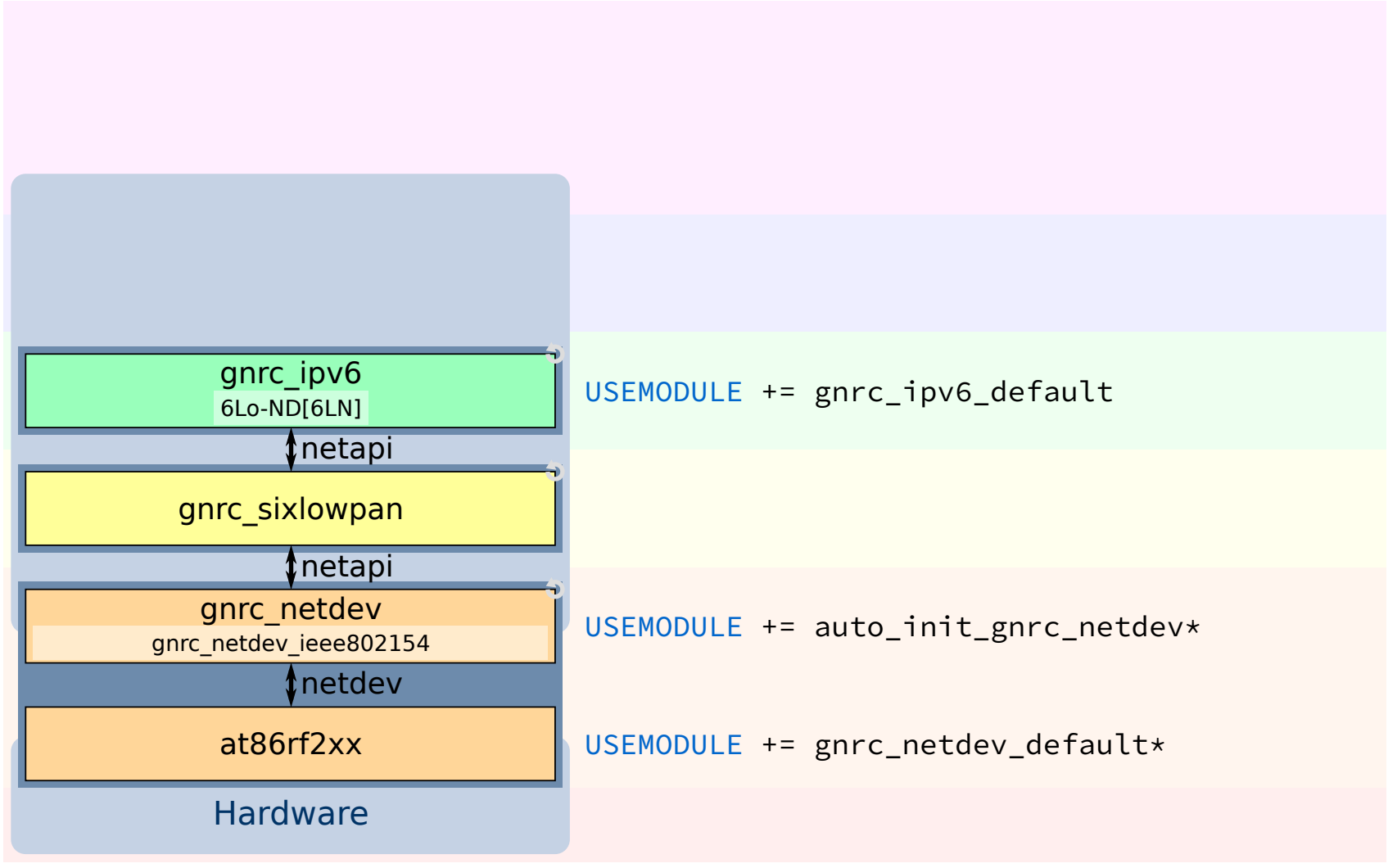
gnrc_minimal example (native)

- * = name might be subject to change



gnrc_minimal example (samr21-xpro)

- * = name might be subject to change



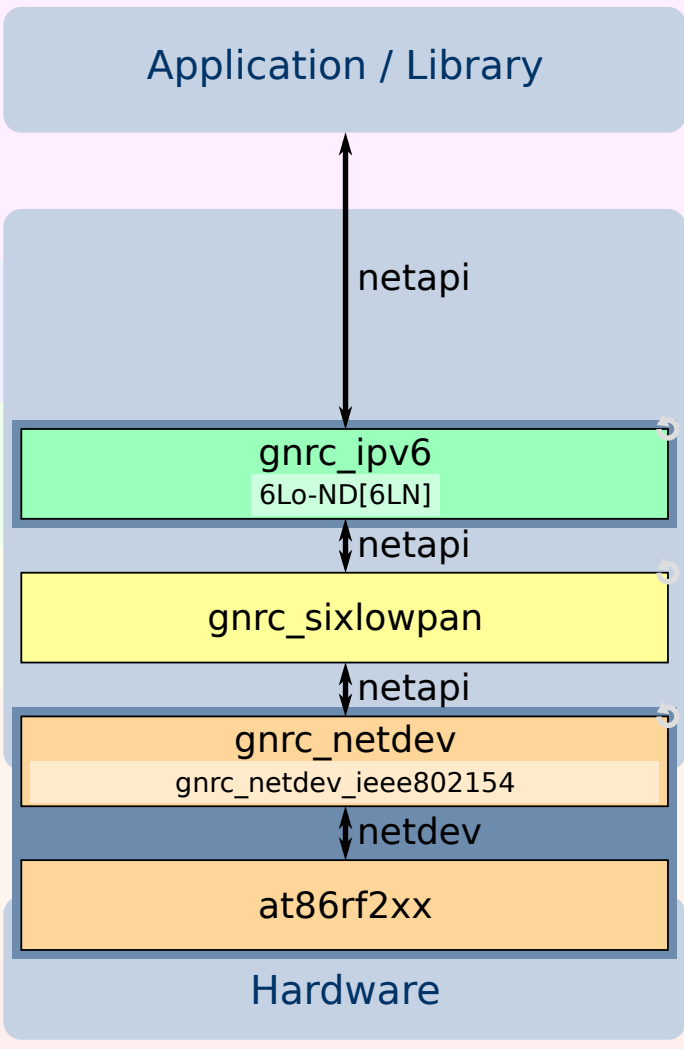
Task 7.1 – Compile the `gnrc_minimial` application

- Go to the `gnrc_minimal` application (`cd gnrc_minimal`)
- Compile and run on `native`
- Should print something like `My address is fe80::d403:24ff:fe89:2460`
- Ping RIOT instance from Linux:

```
ping6 <RIOT-IPv6-addr>%tap0
```

gnrc_minimal example (samr21-xpro)

- Adding a simple application
- $*$ = name might be subject to change




```
gnrc_netreg_t app = {NULL, PROTNUM_NONXT,
                     sched_active_pid};
gnrc_netreg_register(GNRC_NETTYPE_IPV6,
                     &app);
```

```
USEMODULE += gnrc_ipv6_default
```

```
USEMODULE += auto_init_gnrc_netdev*
```

```
USEMODULE += gnrc_netdev_default*
```

Task 7.2 – Extend gnrc_minimal application

- Add the gnrc_udp module to the application
- Register for UDP packets of port 8888

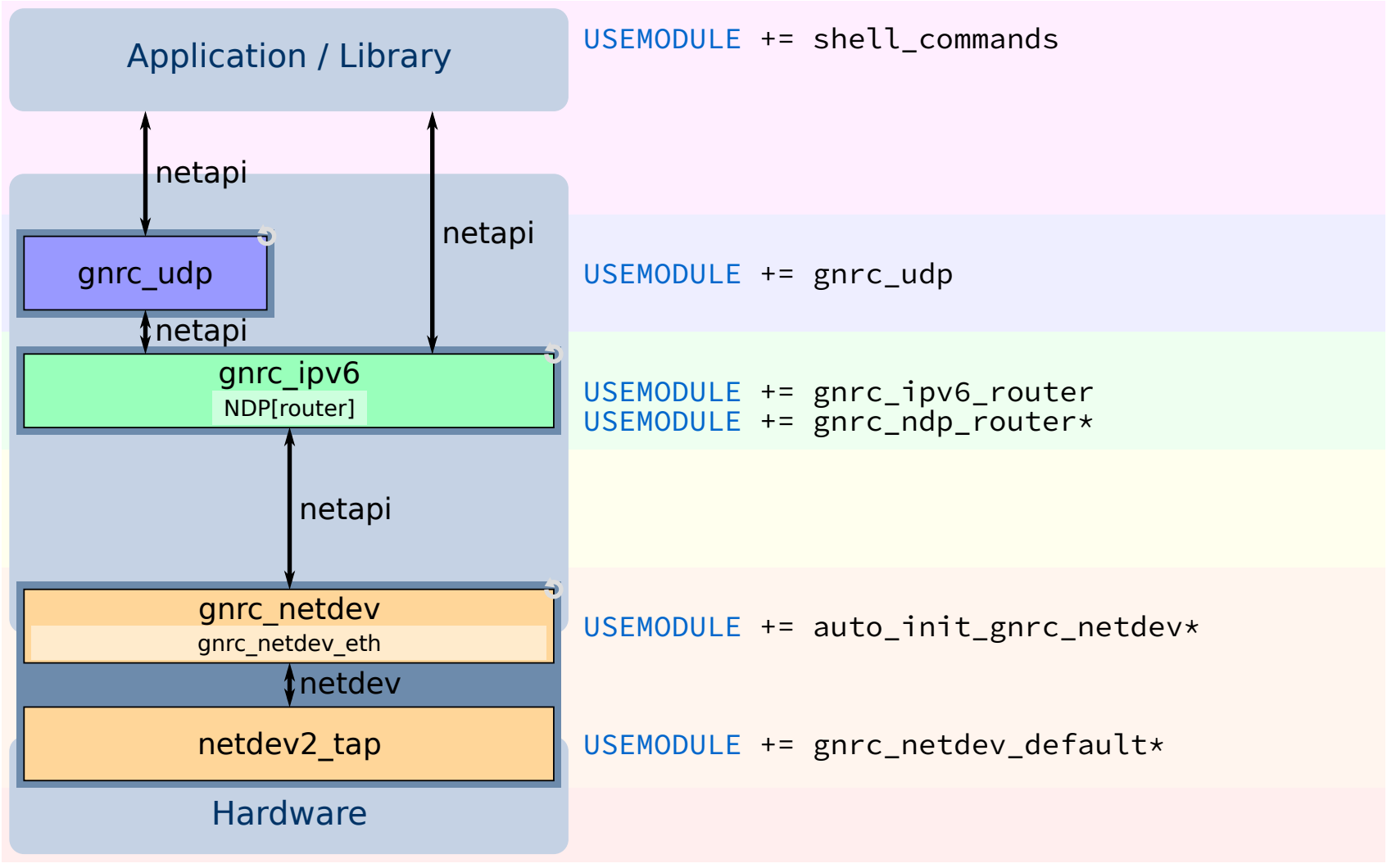
```
/* include "sched.h", "net/gnrc/netreg.h", and "net/gnrc/pktbuf.h"! */
unsigned int count = 0; msg_t msg;
gnrc_netreg_t server = {NULL, 8888, sched_active_pid};
gnrc_netreg_register(GNRC_NETTYPE_UDP, &app);

while (1) {
    gnrc_pktsnip_t *pkt;
    msg_receive(&msg);
    pkt = (gnrc_pktsnip_t *)msg.content.ptr;
    printf("Received %u UDP packets\n", ++count);
    gnrc_pktbuf_release(pkt);
}
```

- Compile and run on native
- Send UDP packet to RIOT node using netcat

```
echo "hello" | nc -6u <RIOT-IPv6-addr>%tap0 8888
```

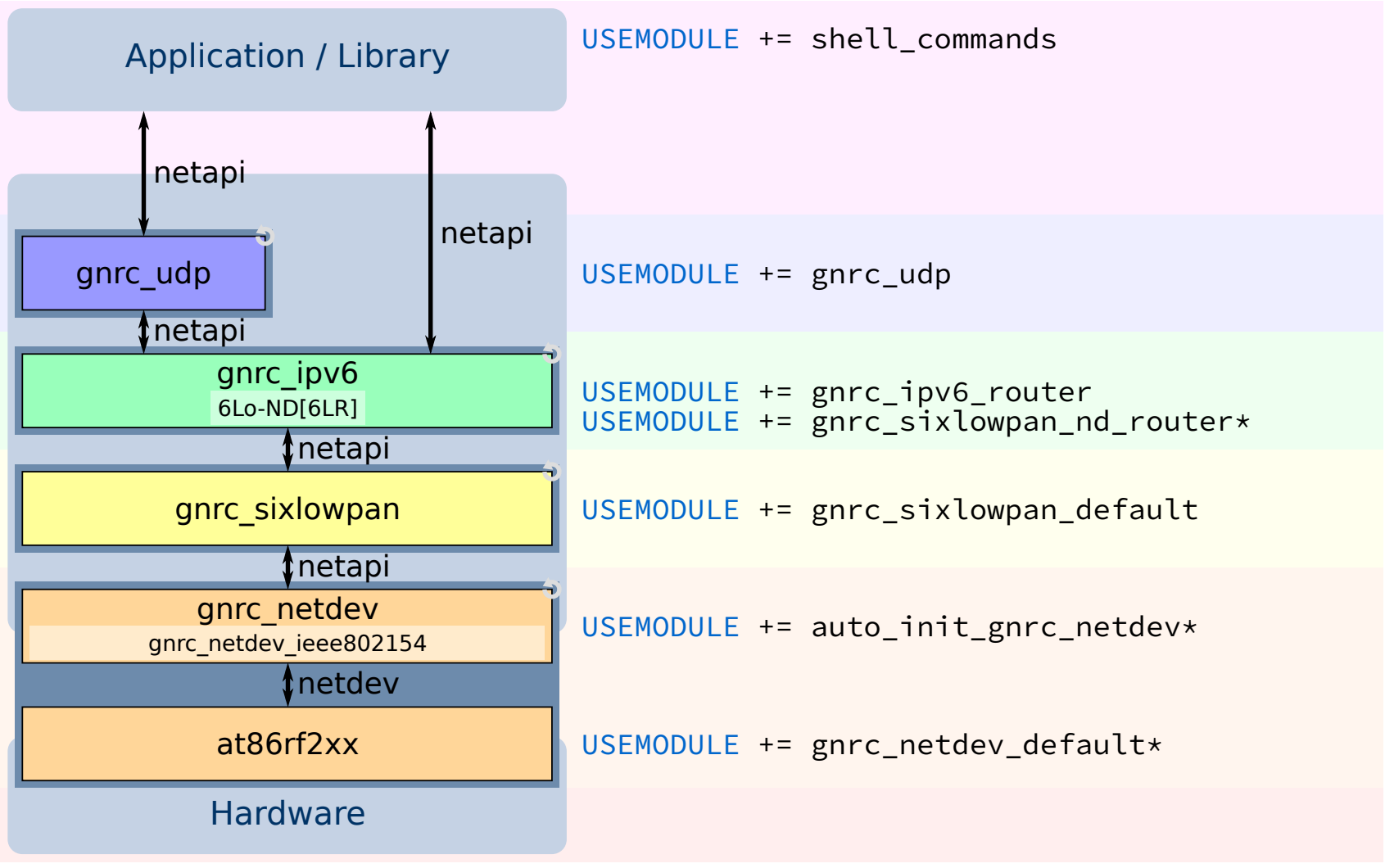
gnrc_networking example (native)

- * = name might be subject to change



gnrc_networking example (samr21-xpro)

- * = name might be subject to change



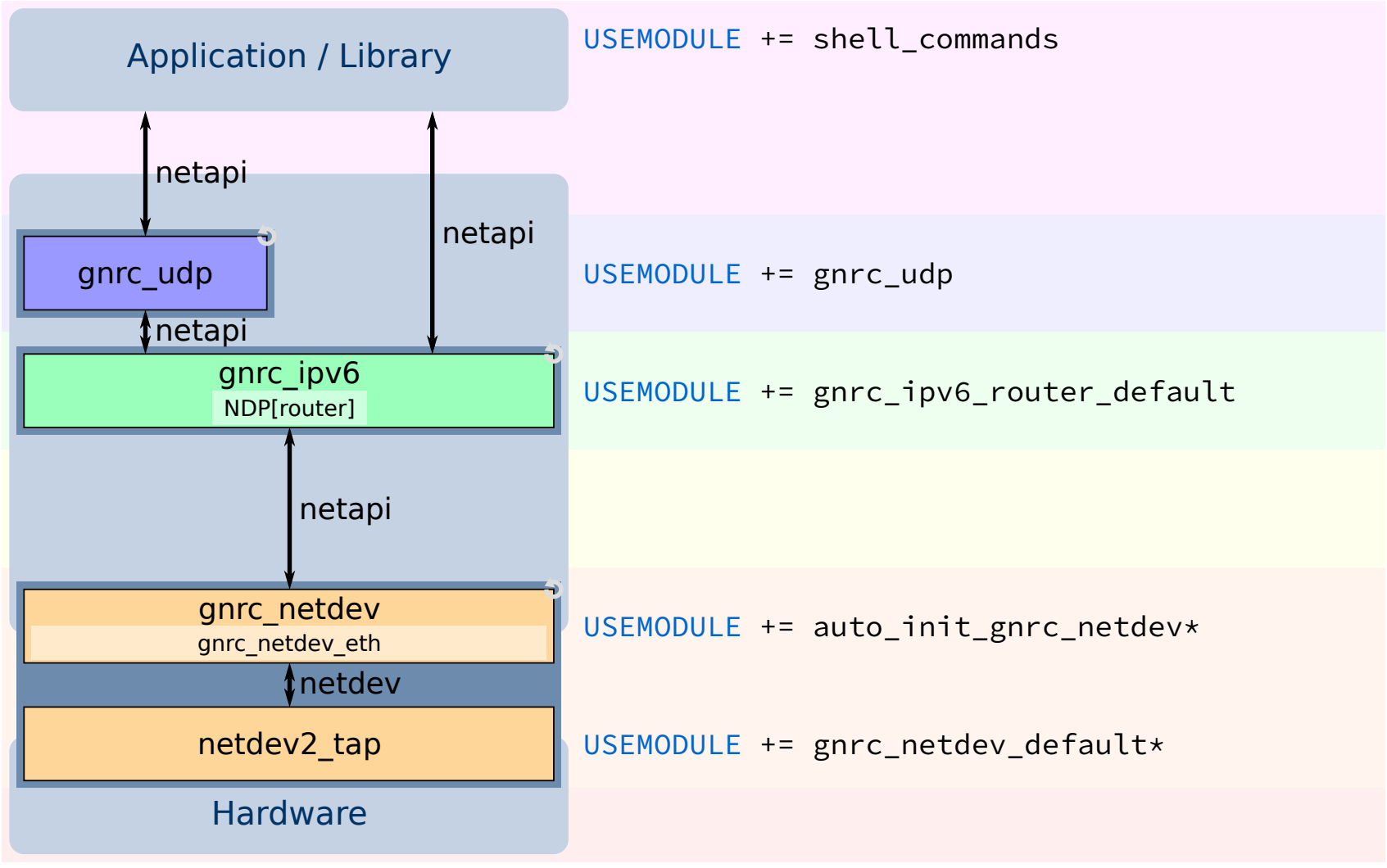
More short-cuts (`Makefile.dep`)

Pseudo-module dependencies

- `gnrc_ipv6_router_default`:
  - `gnrc_ipv6`
  - `gnrc_ndp_router` (if non-6Lo interface present)
  - `gnrc_sixlowpan_default` (if 6Lo interface present)
  - `gnrc_sixlowpan_nd_router` (if 6Lo interface present)

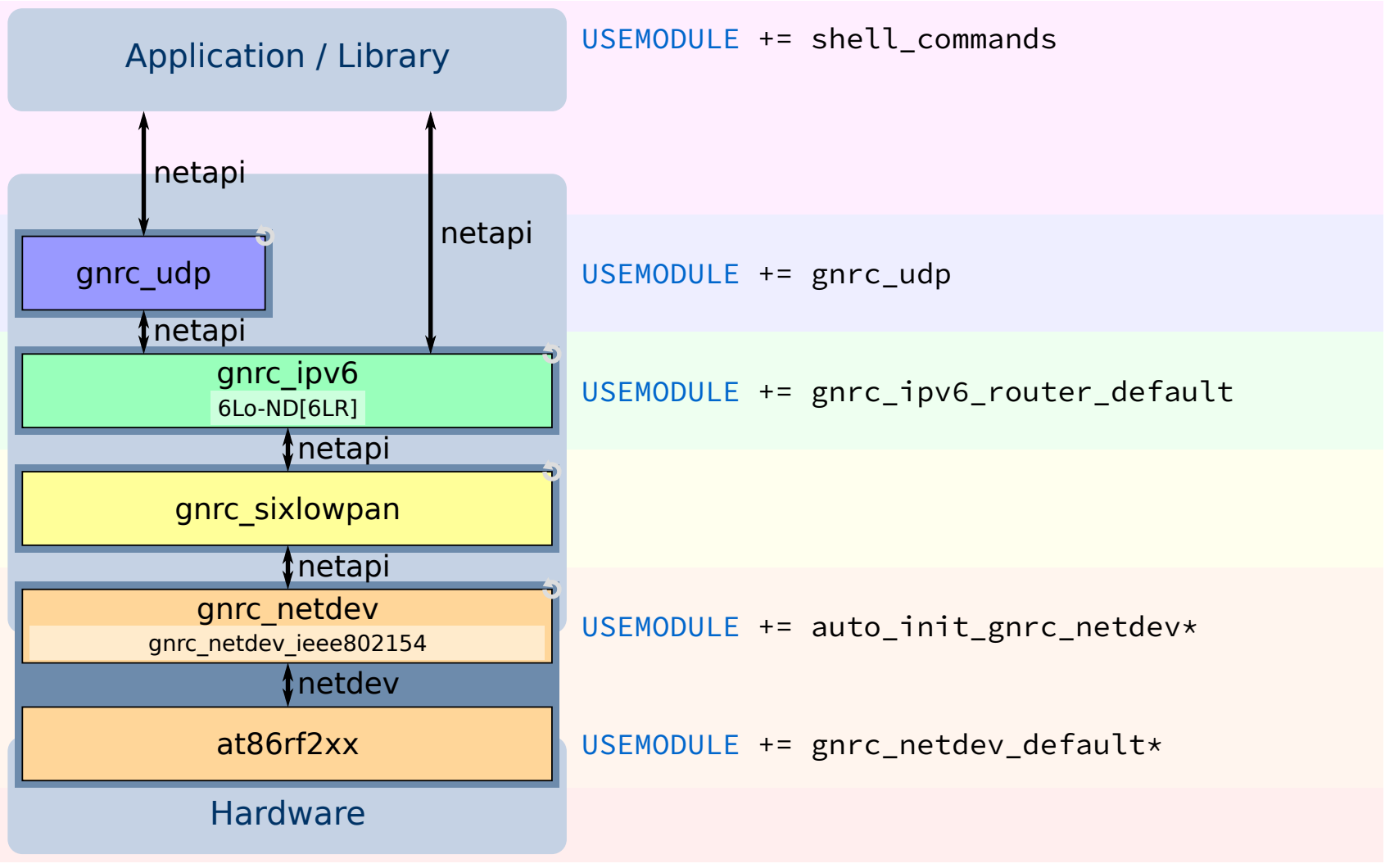
gnrc_networking example (native)

- * = name might be subject to change



gnrc_networking example (samr21-xpro)

- * = name might be subject to change

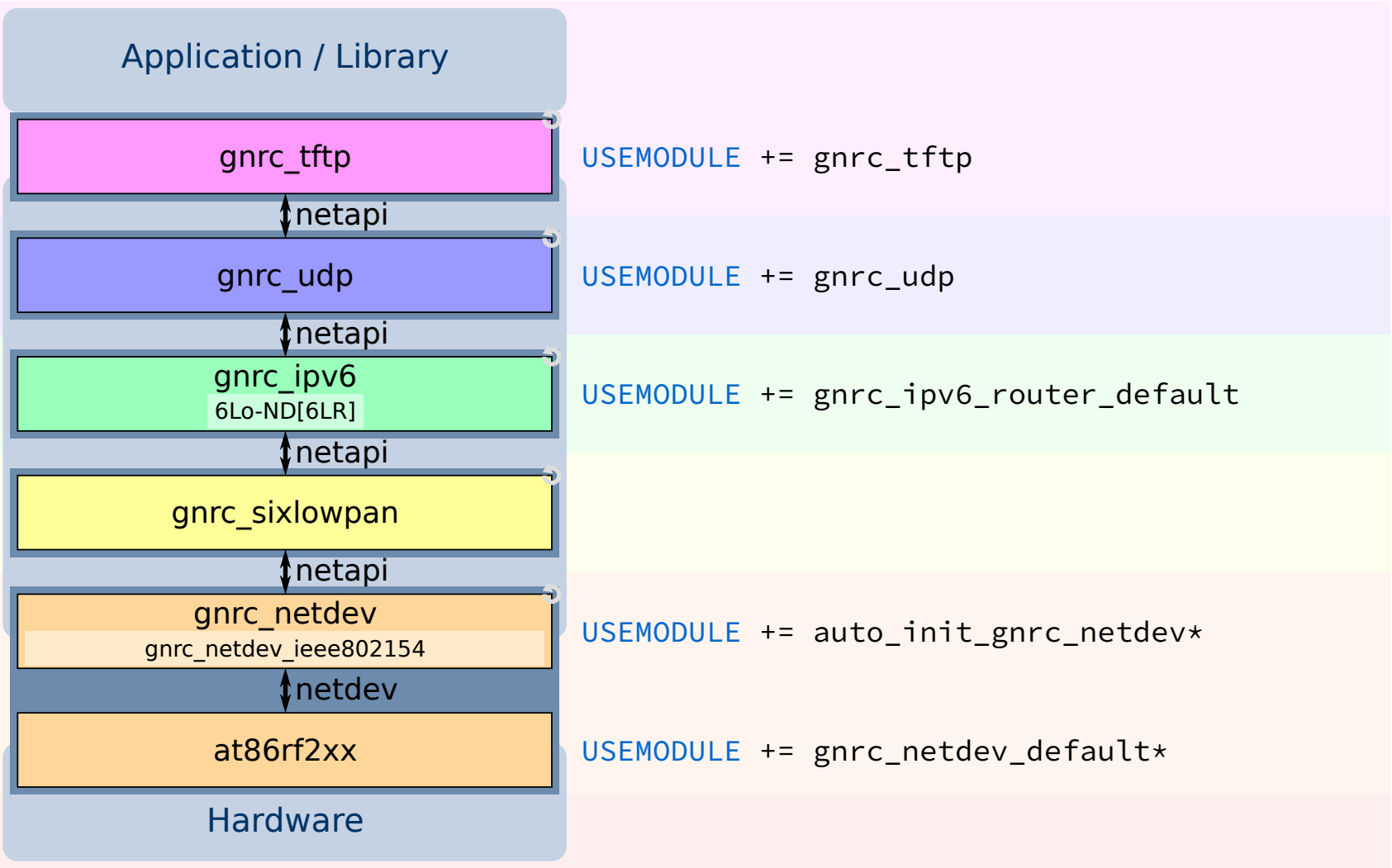


Task 7.3 – Send your neighbor some messages again

- Go to `gnrc_networking` example: `cd ../gnrc_networking`
- Have a look in `udp.c` how packets are constructed and send
- Compile, flash, and run on the board `BOARD=samr21-xpro`
  `make all flash term`
- Type `help`
- Start UDP server on port 8888 using `udp server 8888`
- Get your IPv6 address using `ifconfig`
- Send your neighbor some messages using `udp send`

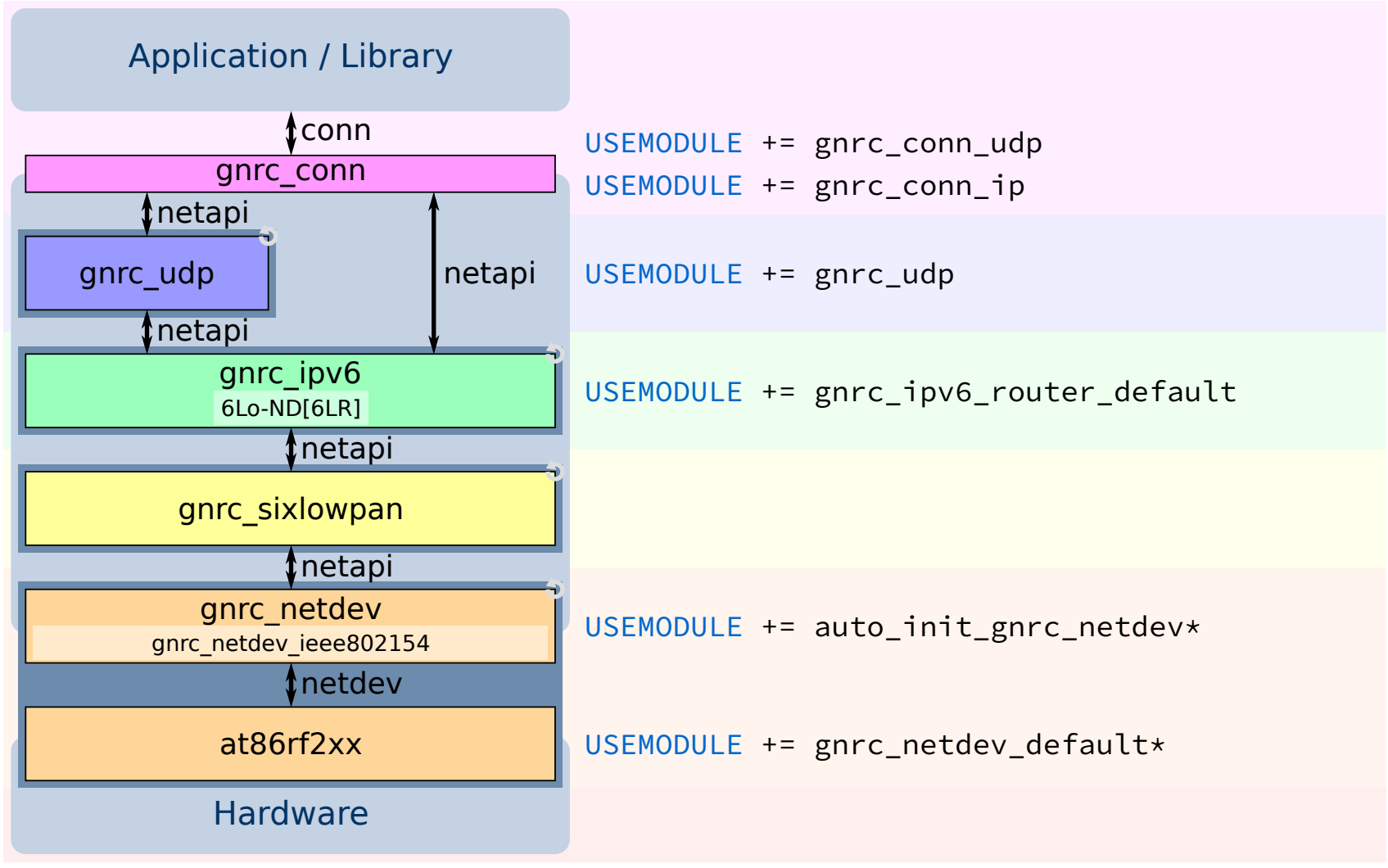
gnrc_tftp example

- for simplicity only the `samr21-xpro` examples from now on
- `*` = name might be subject to change



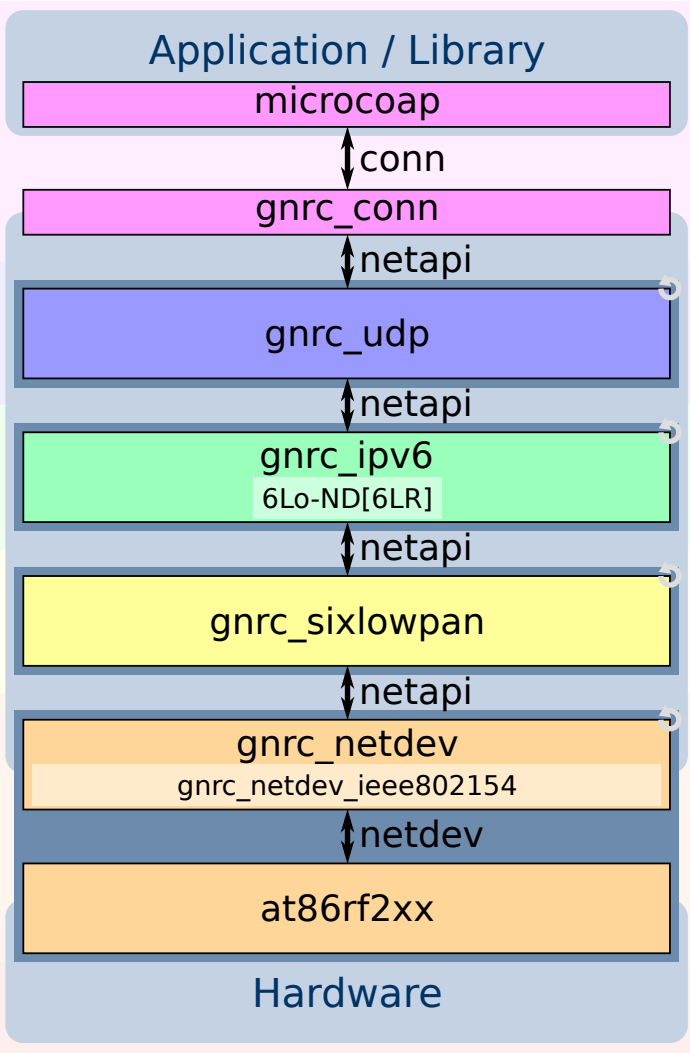
Make your application stack independent

- $*$ = name might be subject to change



microcoap example

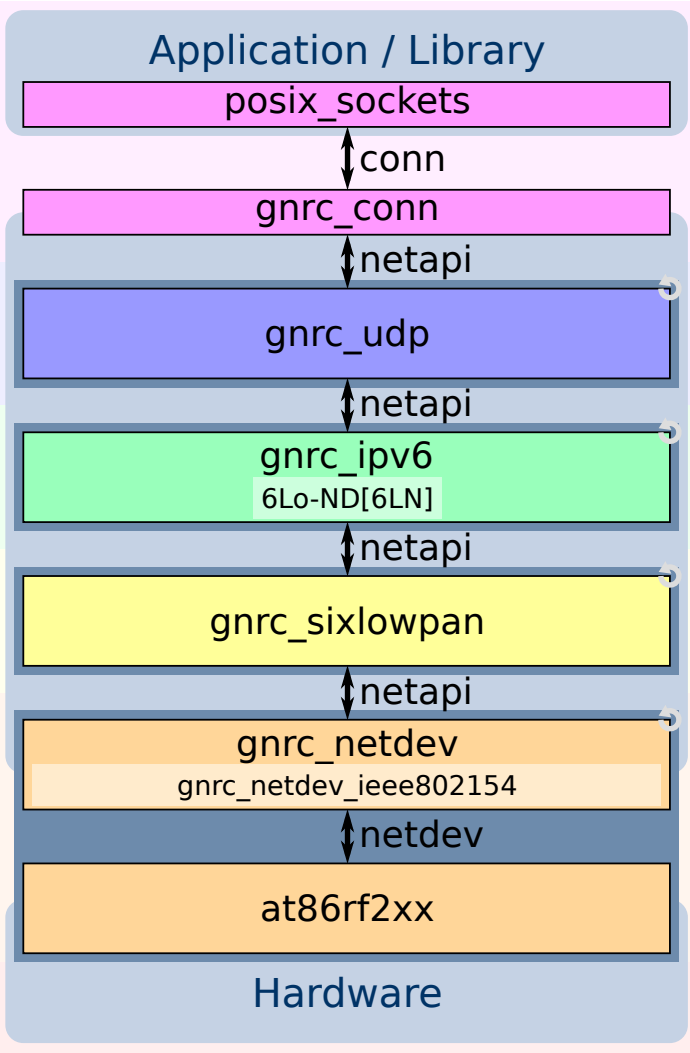
- * = name might be subject to change




```
USEPKG += microcoap
USEMODULE += gnrc_conn_udp
USEMODULE += gnrc_udp
USEMODULE += gnrc_ipv6_router_default
USEMODULE += auto_init_gnrc_netdev*
USEMODULE += gnrc_netdev_default*
```

posix_sockets example

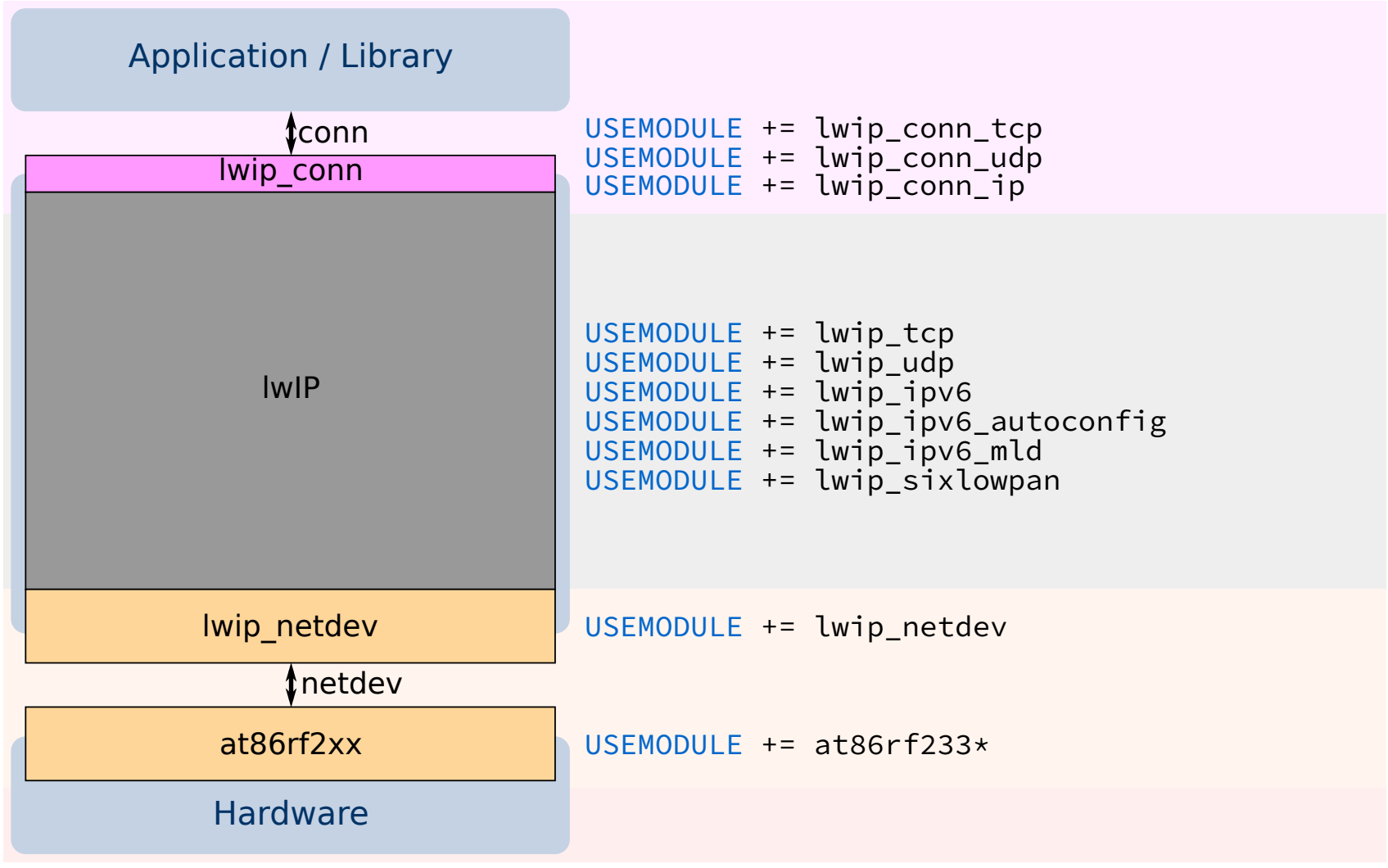
- * = name might be subject to change




```
USEMODULE += posix_sockets
USEMODULE += gnrc_conn_udp
USEMODULE += gnrc_udp
USEMODULE += gnrc_ipv6_default
USEMODULE += auto_init_gnrc_netdev*
USEMODULE += gnrc_netdev_default*
```

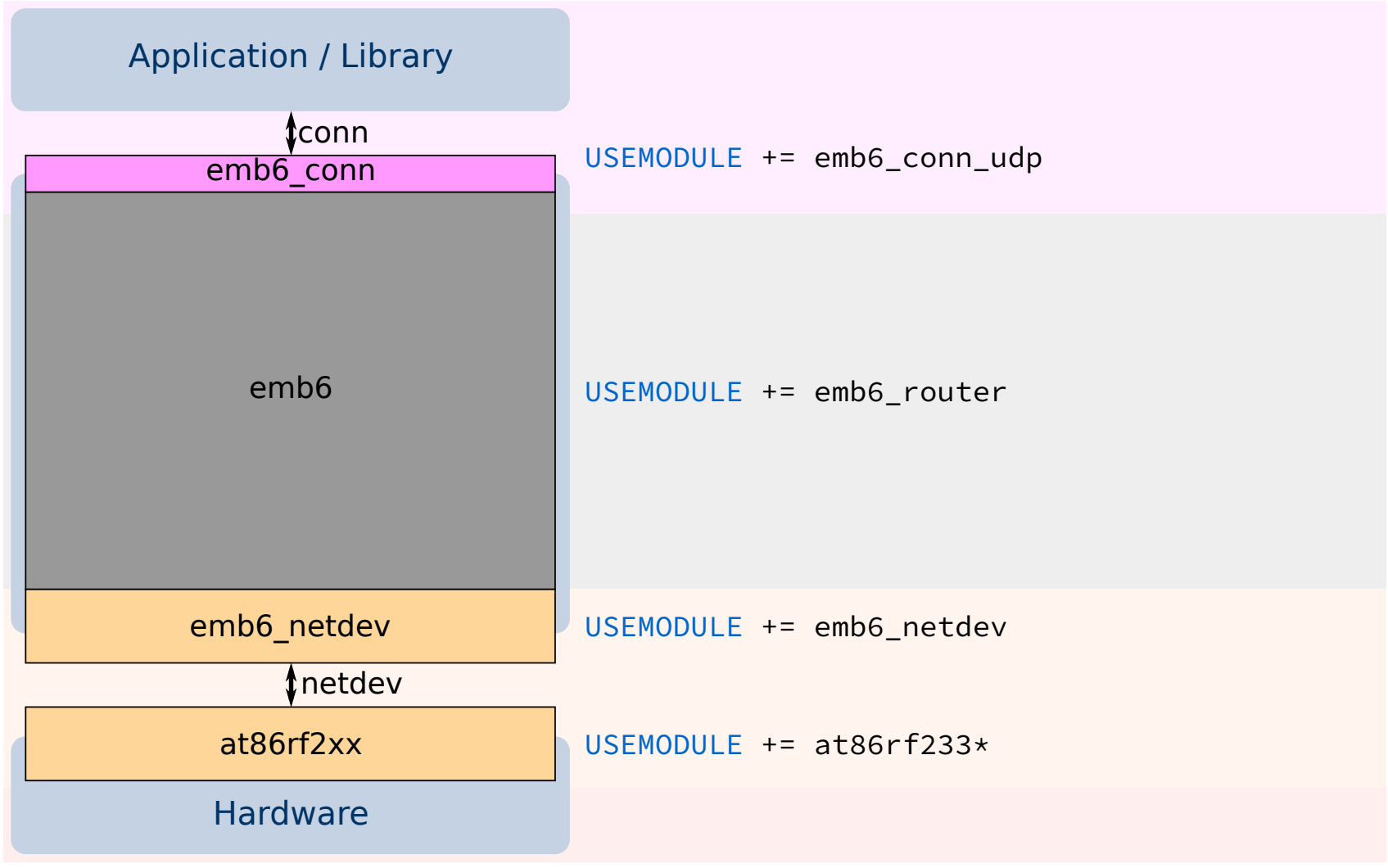
lwIP instead of GNRC

- $*$ = name might differ on other devices



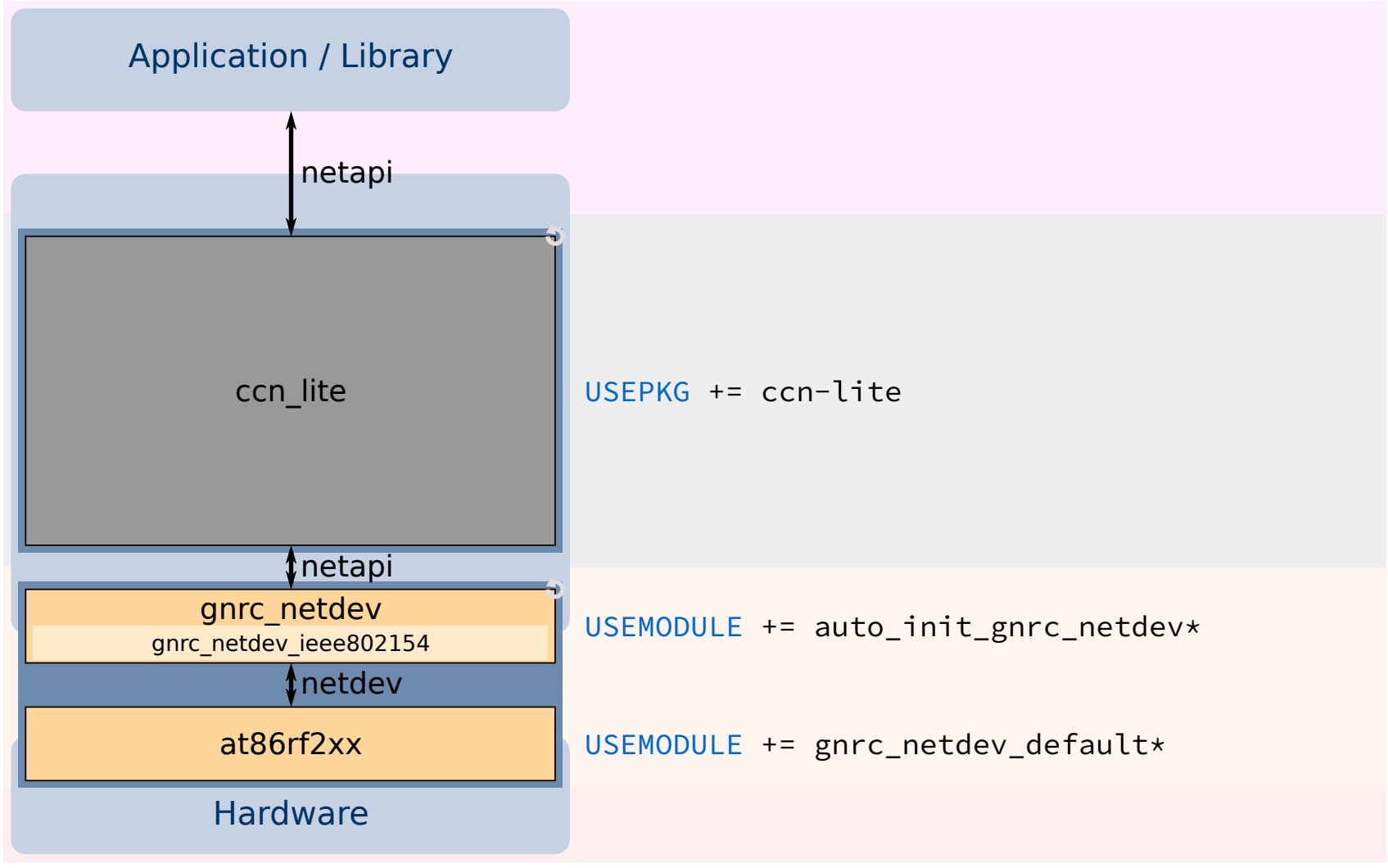
emb6 (uIP-fork) instead of GNRC

- $*$ = name might differ on other devices



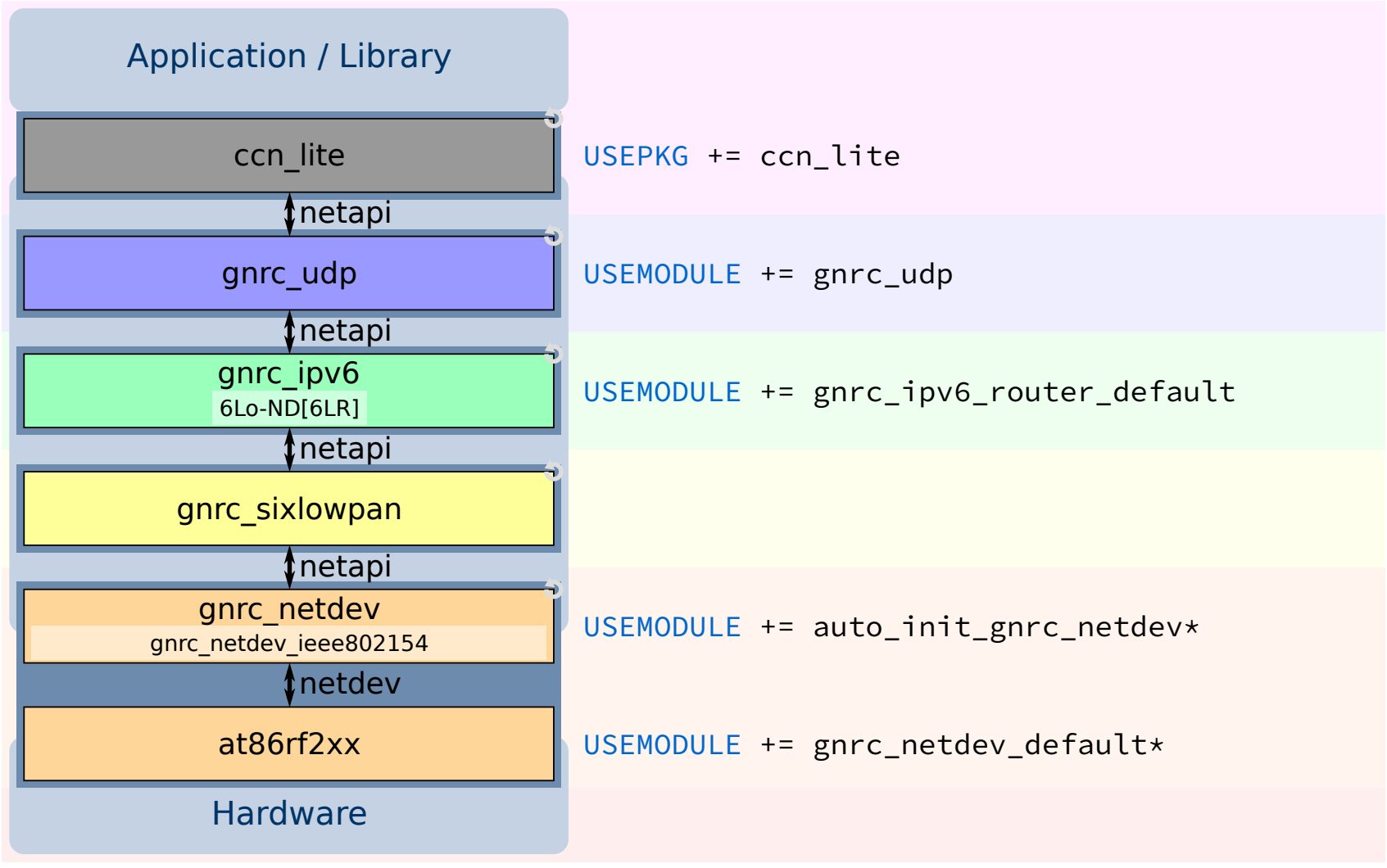
ccn_lite_relay example

- * = name might be subject to change



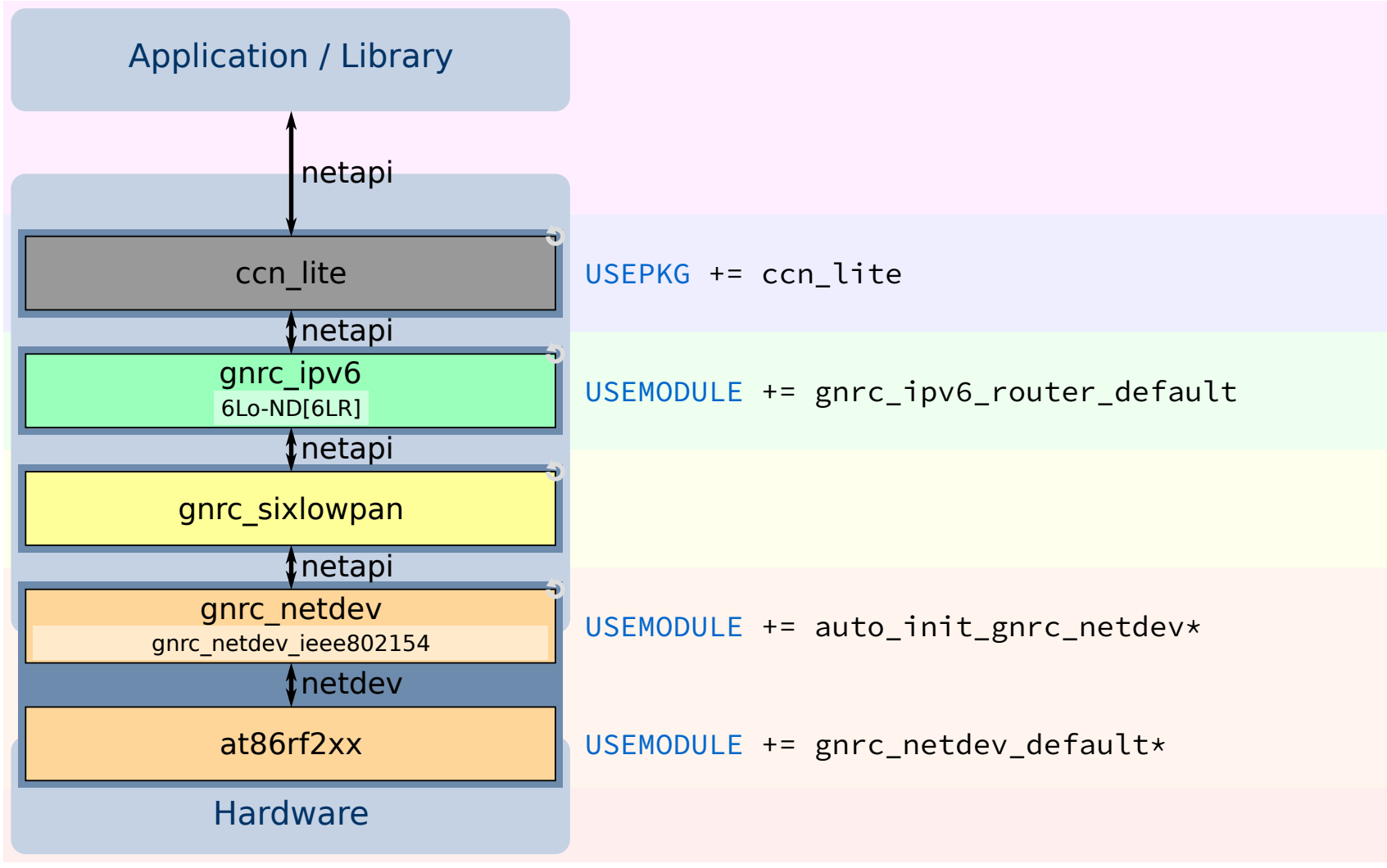
CCN-lite over UDP example

- $*$ = name might be subject to change



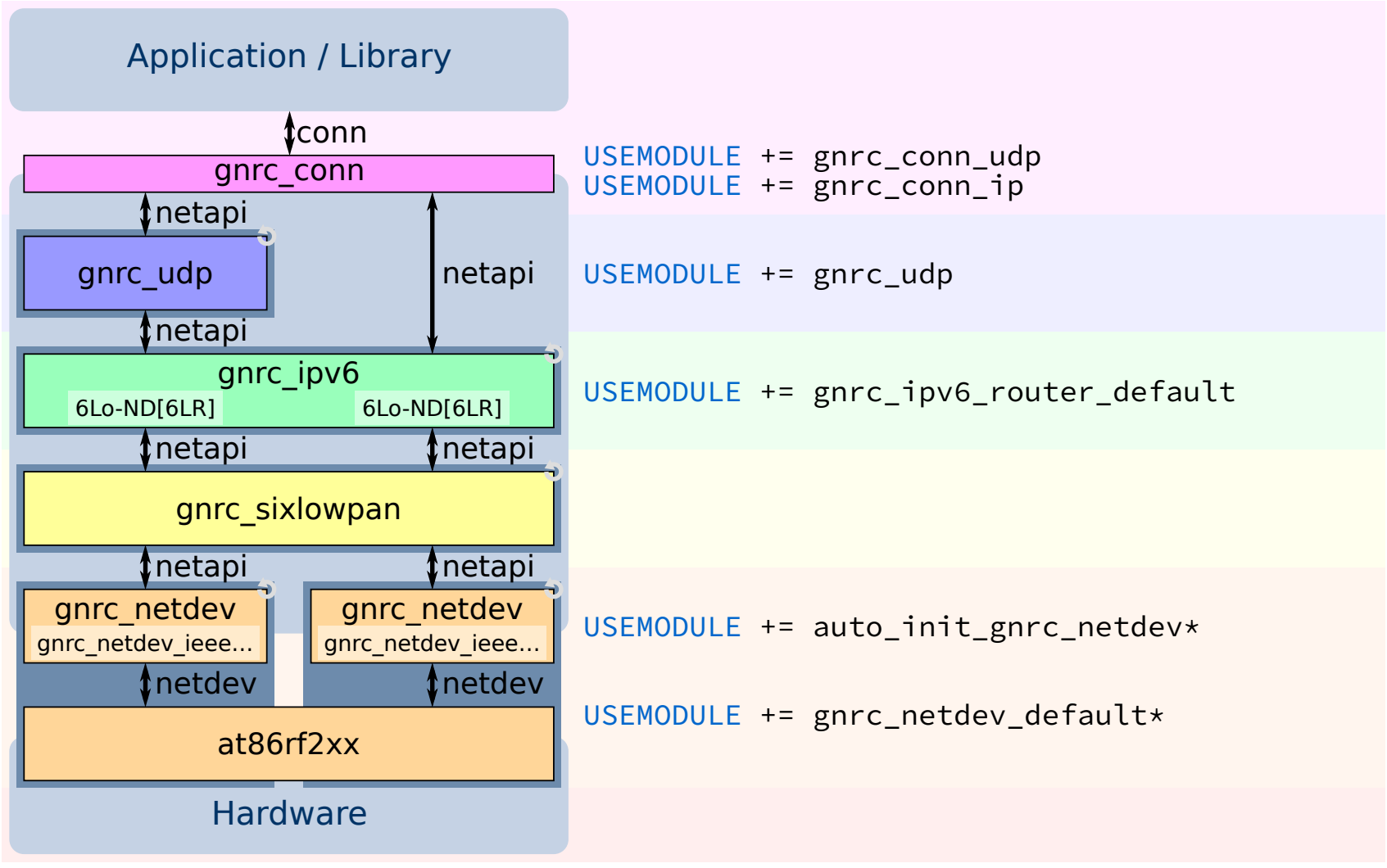
CCN-lite over IPv6 example

- $*$ = name might be subject to change



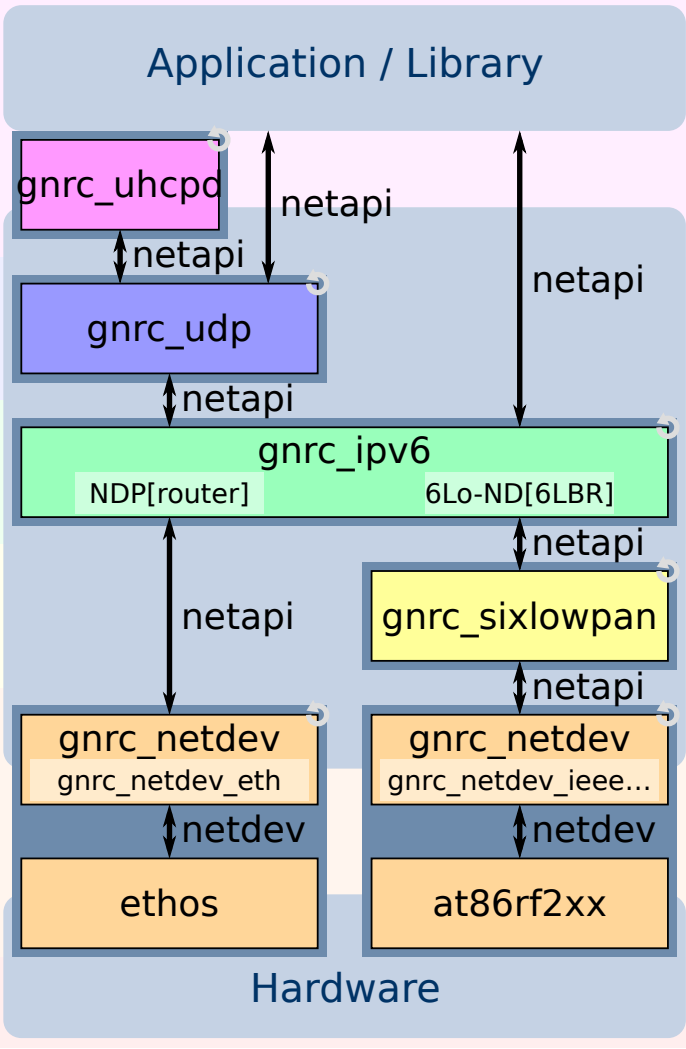
Example: multiple radios of the same type

- $*$ = name might be subject to change



gnrc_border_router example

- * = name might be subject to change




```
USEMODULE += shell_commands
USEMODULE += gnrc_uhcpd
USEMODULE += gnrc_udp
USEMODULE += gnrc_ipv6_router_default
USEMODULE += gnrc_sixlowpan_nd_border_router*
USEMODULE += auto_init_gnrc_netdev*
USEMODULE += gnrc_netdev_default*
```

Now go out and make something!