A Practical Introduction to Sensor Network Programming

Wireless Communication and
Networked Embedded Systems, VT 2011

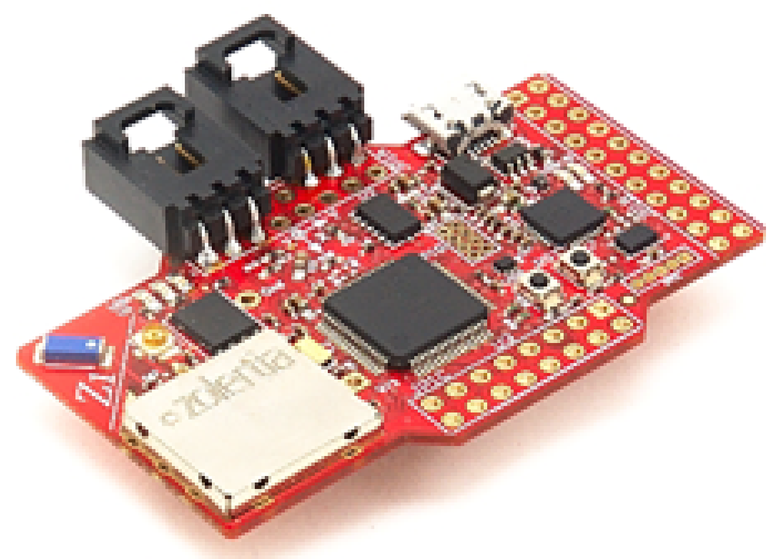
Frederik Hermans,
Communication Research, Uppsala Universitet

Overview

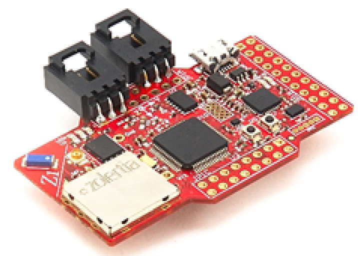
- **Sensor node hardware: Zolertia Z1**
- TinyOS & nesC
  - Components & Interfaces
  - A first TinyOS program: Blink
  - Networking in TinyOS: Active messages
- Contiki
  - Protothreads
  - A first Contiki program: Blink
  - Networking in Contiki: The Rime stack
- Wrap-up

Zolertia Z1

- General purpose sensor node for research
- Low power consumption
  - Months to years on two AA batteries
- Specs
  - 16 MHz, 8 kB RAM
  - Radio: 250 kbps @ 2.4 GHz
  - Three LEDs
  - Accelerometer
  - Temperature sensor



Some perspective on the specs



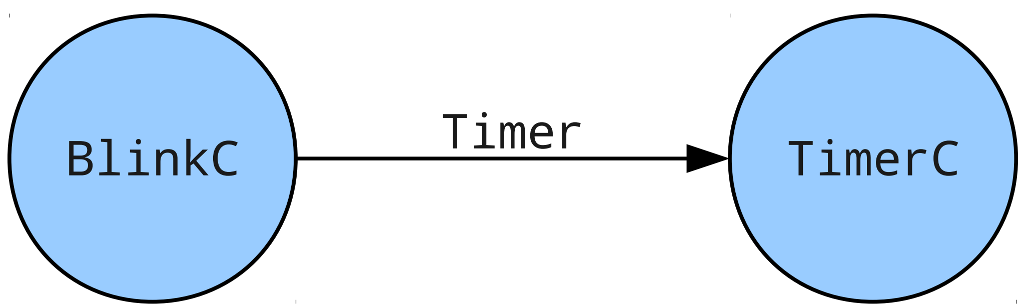
Clock speed	16 MHz	4 MHz	1024 MHz
RAM	8 kB	8 kB	589824 kB
Program size	92 kB	8192 kB	~ 409600 kB
Radio	250 kbps	N/A	55296 kbps
Lifetime	Months to years	A few days	A few days

TinyOS

- OS designed for low-power wireless devices
  - Large community
  - Open source (BSD license)
- Event-based
  - Split-phase operations instead of blocking
- TinyOS programs are written in nesC
- Allows to create really tiny programs
  - Heavy optimization for size

nesC: Components

- A nesC program consists of **components**
- There are two types of components
  - A **module** implements some program logic
  - A **configuration** wires different modules together
- Components may use or provide **interfaces**



nesC: Interfaces

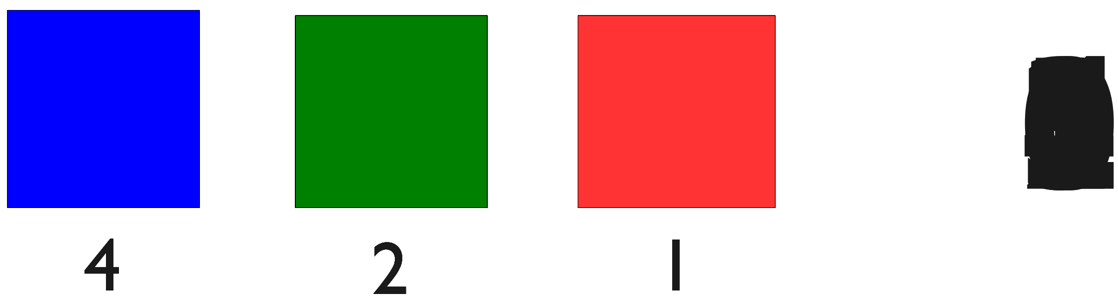
- An interface describes a behavior (cf. Java)
- It specifies **commands** and **events**
- Example:

```
interface Timer {
  command void start(uint32_t dt);
  event void fired();
}
```

- If a module uses an interface, then it *may call* its commands and it *must handle* its events
- If a module provides an interface, then it *must implement* its command and it *may signal* its events

A first TinyOS program: Blink

- Increase a counter every second
- Make LEDs show last three bits of counter



- Need to write two components
  - A module to contain our program logic
  - A configuration that wires our module to other modules in TinyOS

BlinkC: The module

```
module BlinkC {
  uses interface Boot;
  uses interface Timer<TMilli>;
  uses interface Leds;
}

implementation {
  int counter = 0;

  event void Boot.booted() {
    call Timer.startPeriodic(1024);
  }

  event void Timer.fired() {
    counter++;
    call Leds.set(counter);
  }
}
```

Timer interface to generate an event every second

For controlling LEDs

Gets called when Boot signals boot() event

Call command startPeriodic(...)

Gets called when Timer

Increase counter and call command set(...)

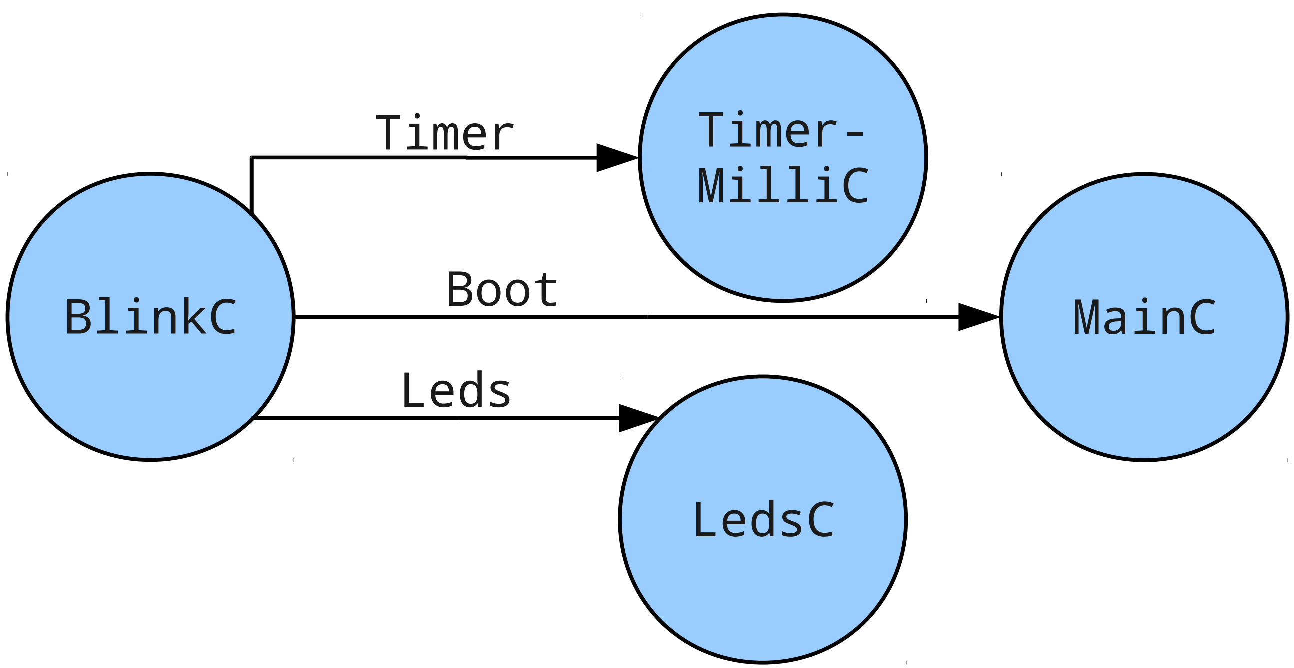
BlinkC: The configuration

```
configuration BlinkAppC { }

implementation {
  components MainC, BlinkC, LedsC, new TimerMilliC();

  BlinkC.Boot -> MainC;
  BlinkC.Timer -> TimerMilliC;
  BlinkC.Leds -> LedsC;
}
```

Our program will use these components

TimerMilliC provides Timer<TMilli>

LedsC provides Leds



Genericity

```
configuration BlinkAppC { }

implementation {
  components MainC, BlinkC, LedsC, new TimerMilliC();

  BlinkC.Boot -> MainC;
  BlinkC.Timer -> TimerMilliC;
  BlinkC.Leds -> LedsC;
}
```

- Components are **singleton** or **generic**
  - Generic components need to be instantiated
  - Generic components can take arguments
- Interfaces can also be generic
  - E.g., the `Timer<precision>` interface

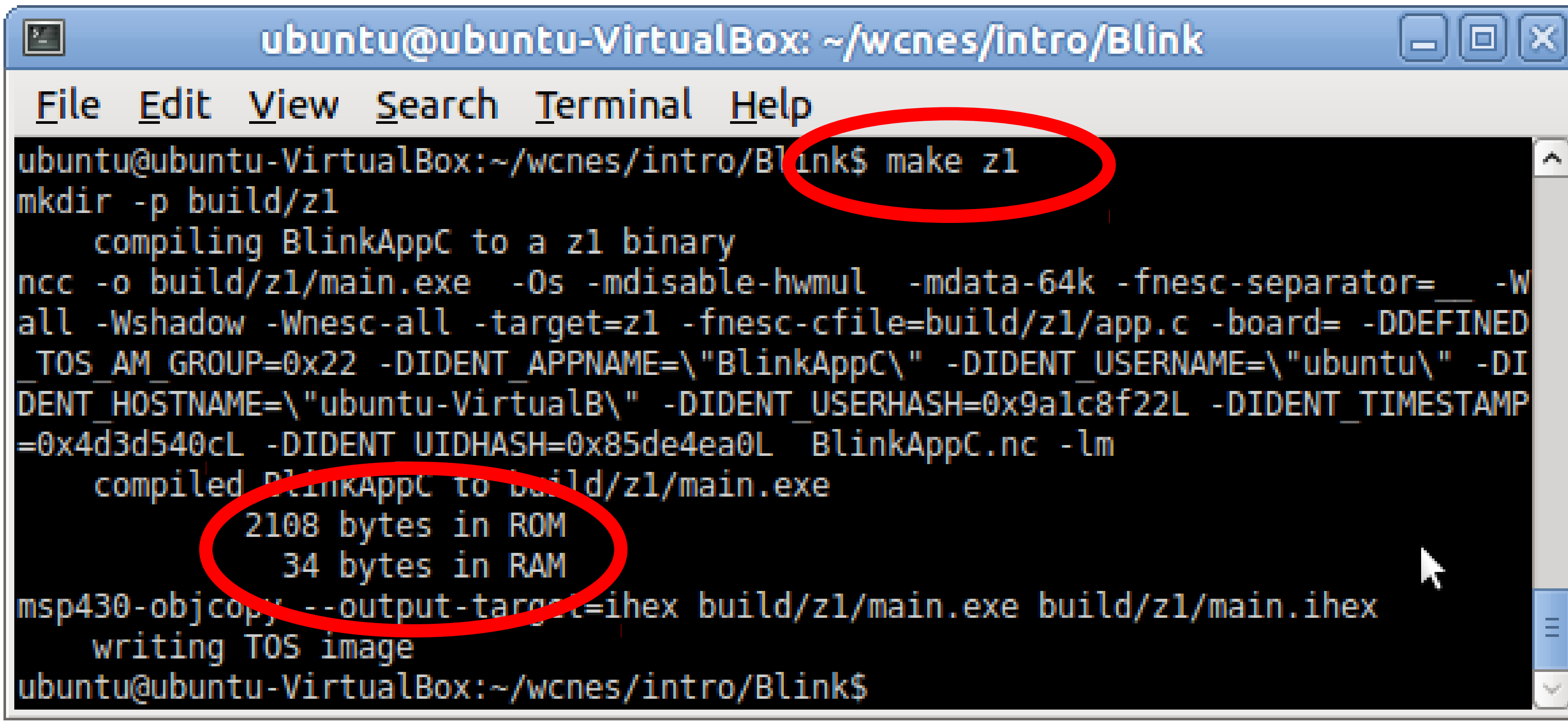
Blink: Programming nodes

- Next steps: Build and upload
  - Need a compiler and linker suitable for target architecture
  - Need a standard library for our target architecture
  - Need TinyOS sources

- Virtual machine image with everything pre-installed
  - Will be uploaded to the course page soon™
  - Use it!

Blink: Creating a binary

- Open a shell, change into the project directory, and run `make Z1`



Blink: Uploading the binary

- Connect the node using a USB cable
- In the project directory, run `make z1 install`

ubuntu@ubuntu-VirtualBox: ~/wcnes/intro/Blink

File Edit View Search Terminal Help

```
    installing z1 binary using bsl
z1-bsl --z1 -c /dev/ttyUSB1 -r -e -I -p build/z1/main.ihex.out
MSP430 Bootstrap Loader Version: 1.39-goodfet-8
Mass Erase...
Transmit default password ...
Invoking BSL...
Transmit default password ...
Current bootstrap loader version: 2.13 (Device ID: f26f)
Changing baudrate to 38400 ...
Program ...
2172 bytes programmed.
Reset device ...
rm -f build/z1/main.exe.out build/z1/main.ihex.out
ubuntu@ubuntu-VirtualBox:~/wcnes/intro/Blink$
```

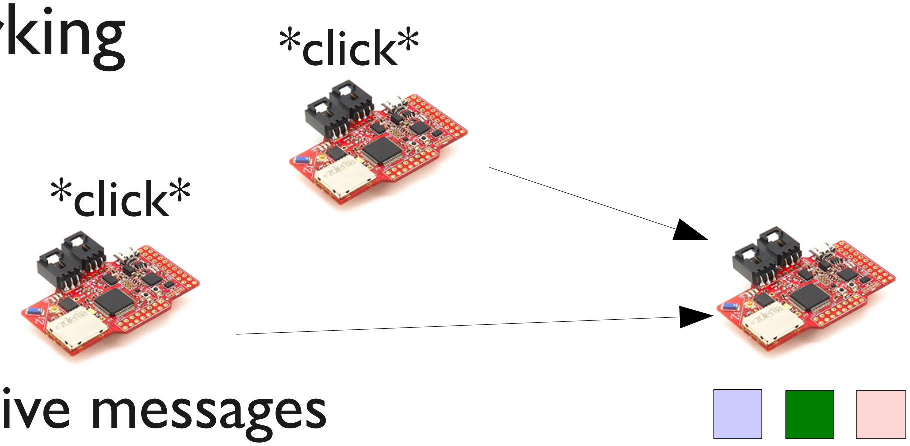
Overview

- Sensor node hardware: Zolertia Z1
- TinyOS & nesC
  - Components & Interfaces
  - A first TinyOS program: Blink
  - **Networking in TinyOS: Active messages**
- Contiki
  - Protothreads
  - A first Contiki program: Blink
  - Networking in Contiki: The Rime stack
- Wrap-up

A first networked TinyOS program

- Clickers are real products
  - Used for audience response

- How does our simple clicker work?
  - Learn about TinyOS networking
  - Two types of nodes
    - Clients, base station
  - We need to
    - Turn on radio, send, and receive messages



TinyOS active messages

- Basic networking abstraction: Active message
  - Single-hop, best-effort radio communication
  - Each active message has (among other stuff)
    - Destination address
    - Type (similar to UDP port)
    - Payload
  - Building block for more complex communication services
- Interfaces to turn on/off radio, manipulate, send and receive active messages

Active messages: Interfaces

- Relevant interfaces
  - `SplitControl` – start/stop the radio
  - `Packet` – manipulate a packet
  - `AMSend` – send packets
  - `Receive` – receive packets
- For details, see TEP 116

Active messages: Components

- Which components implement the interfaces?
  - `ActiveMessageC` provides `SplitControl`
  - `AMSenderC` provides `AMSend` and `Packet`
  - `AMReceiverC` provides `Receive`

- `AMSenderC` and `AMReceiverC` are generic
  - Need to be instantiated
  - Constructor takes on argument: An active message type
  - E.g., `component new AMReceiveC(42)`

Active messages: Starting the radio

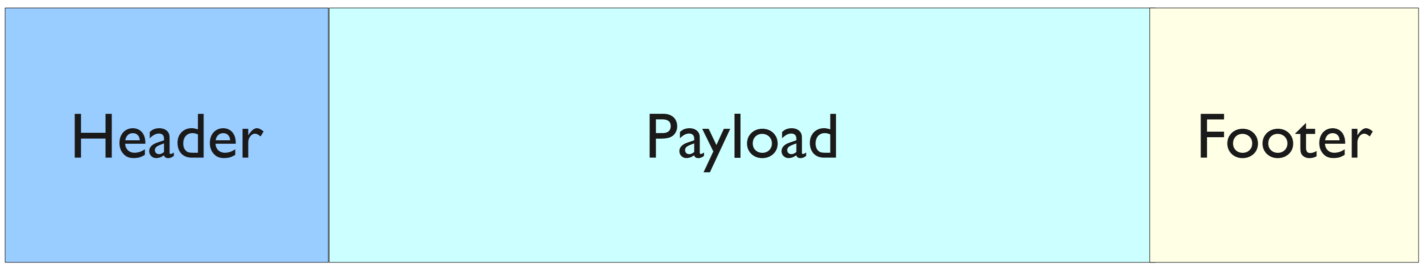
- ActiveMessageC provides SplitControl to turn on/off radio
  - Signals events `startDone(err)` and `stopDone(err)`

```
module ClickerClientC { uses interface SplitControl; ... }

implementation {
  event void Boot.booted() {
    call SplitControl.start();
  }

  event void SplitControl.startDone(error_t err) {
    if (err == SUCCESS) { /* We can use active messages now */ }
    else { call SplitControl.start(); }
  }

  event void SplitControl.stopDone(error_t err) { }
}
```

Start the radio

Active messages: Packets

- A packet is stored in a variable of type `message_t`
  - Contains type, destination, payload, ...



- Packets may look different on different platforms
  - Therefore, a packet must never be modified by changing the fields of `message_t` directly
  - Instead, use the functions provided by the `Packet` interfaces
  - E.g., `Packet.getPayload(msg, len)`

Active messages: Type and payload

- Need to define active message type and structure of payload
  - Type: Positive integer (cf. UDP port number), e.g. 42
  - Payload: Not really needed for our application
    - Let's send the string “Hej”, just for the sake of it

```
enum { AM_CLICKER_MSG = 42 };

nx_struct clickerMsg_s {
  nx_uint8_t string[4];
};

typedef nx_struct clickerMsg_s clickerMsg;
```

Type that identifies packets of our application

Structure to hold

Assign name clickerMsg to the struct

- (nx_ prefix to ensure correct endianness across platforms)

Active messages: Sending a packet

- `AMSend` provides `command error_t send(...)`
  - Note: `send(...)` immediately returns whether *initiating* the sending was successful
  - Split-phase operation, signals `event void sendDone()` on completion
  - Need to make sure we're not sending another packet, while a packet is still in transmission

Active messages: Sending a packet, pt. 2

```
implementation {
  bool radioBusy = FALSE;
  message_t pkt;

  void send() {
    error_t result;
    ClickerMsg *clickPl;

    if (radioBusy) return;

    clickPl = (ClickerMsg *) (call Packet.getPayload(&pkt,
                                     sizeof(ClickerMsg)));
    memcpy(clickPl->string, "Hej", 4);

    result = call AMSend.send(AM_BROADCAST_ADDR, &pkt,
                              sizeof(ClickerMsg));

    if (result == SUCCESS) radioBusy = TRUE;
  }

  ...
```

Keep track of whether

Packet to b

pkt

Header

Payload

Footer

To store w

send succeeded

clickPl

Set clickPl to point to the payload of pkt

ady?

Broadcast the packet

cket

Update radio state

Active messages: Sending a packet, pt. 3

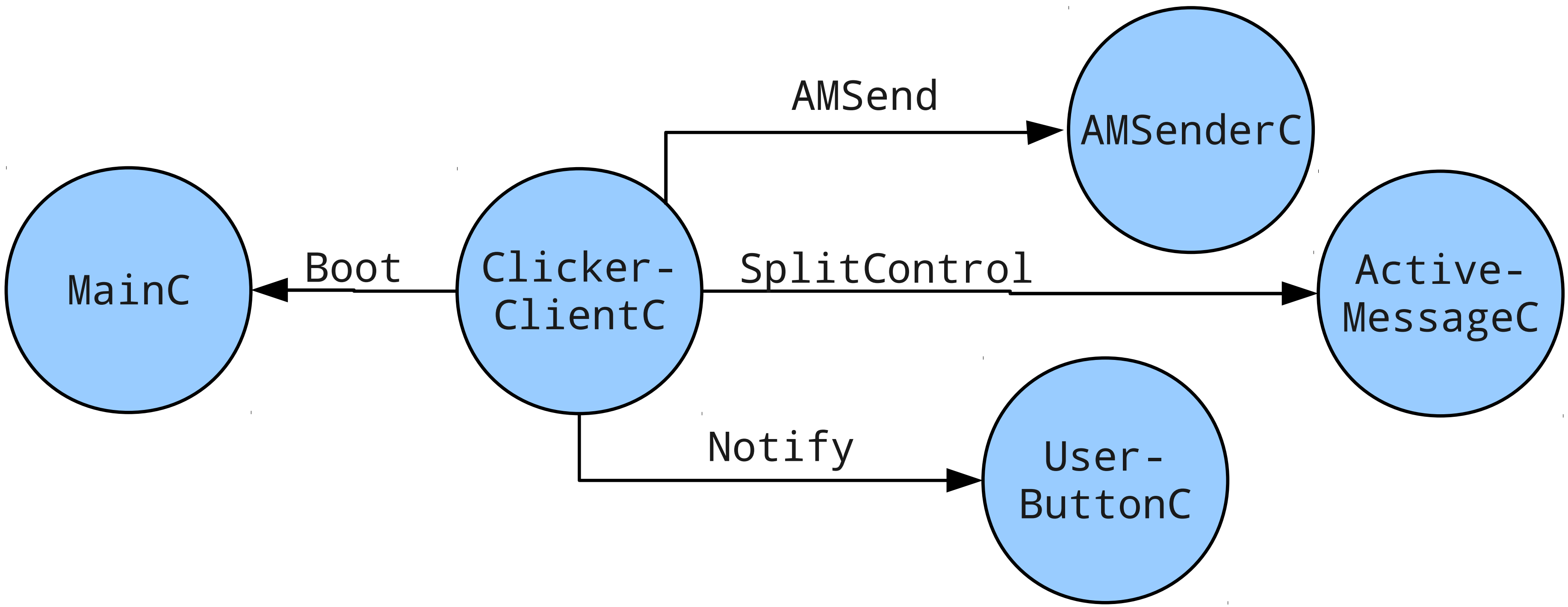
- Still need to handle `sendDone()` event

```
  ...
  event void AMSend.sendDone(message_t *p, uint8_t len) {
    if (p == &pkt) {
      radioBusy = FALSE;
    }
  }
}
```

User button

- Need to send a packet when button pressed
- Component `UserButtonC` provides interface Notify<button_state_t>
  - `command error_t enable()`
  - `event void notify(button_state_t state)`
    - `state: BUTTON_PRESSED` or `BUTTON_RELEASED`

Clicker: Client



- Complete source code at course page

Active messages: Receiving packets

- Receiving is much simpler :)
- Use the Receive interface
  - `event message_t *receive(...)`
  - Note: receive event has a return value

```
implementation {
  ...
  int numReceivedPkts;

  event message_t *Receive.receive(message_t *pkt,
                                   void *payload, uint8_t len) {
    if (len != sizeof(ClickerMsg)) return pkt;

    numReceivedMsgs++;
    call Leds.set(numReceivedMsgs);
    return pkt;
  }
}
```

Sanity check: Is this a packet we expect?

Return pointer to packet buffer

Overview

- Sensor node hardware: Zolertia Z1
- TinyOS & nesC
  - Components & Interfaces
  - A first TinyOS program: Blink
  - Networking in TinyOS: Active messages
- **Contiki**
  - Protothreads
  - A first Contiki program: Blink
  - Networking in Contiki: The Rime stack
- Wrap-up

Contiki

- OS for low-memory networked embedded systems
  - Developed primarily at SICS
  - Open source (BSD license)
- Key features
  - Protothreads allow thread-style programming
  - Strong support for IPv4 and IPv6
- Contiki programs are written in C
  - No need to learn a new language
  - But some preprocessor “magic” involved

Protothreads: Motivation

- Problem: Complex flow of control in an event-driven program
- Example: Stop-and-wait sender

```
void reliableSend(pkt) {
  call Unreliable.send(pkt);
}
```

```
event void Unreliable.sendDone(pkt) {
  call Timer.start(timeout);
}
```

```
event void Timer.fired() {
  call Unreliable.send(pkt);
}
```

```
event void Receiver.receive(r) {
  if (is_ack(r)) call Timer.stop();
}
```

Protothreads: Example

- Protothreads allow thread-style programming for resource-constrained systems

```
PROCESS_THREAD(reliable_sender, …) {
  PROCESS_THREAD_BEGIN();

  do {
    PROCESS_WAIT_UNTIL(data_to_send());
    send(pkt);
    timer_start();
    PROCESS_WAIT_UNTIL((ack_received() || timer_expired());
  } while (!ack_received());

  PROCESS_THREAD_END();
}
```

- Program flow more intuitive for most people

Protothreads

- Regular threads are resource demanding
  - At least if you only have 8 kB of RAM
  - Require OS too keep state of all threads
- Protothreads are very light-weight
  - Threads don't have their own stack!
  - Only two bytes of RAM overhead per thread
  - Suitable for a sensor node with 8 kB of RAM
- *Cave*: Threads don't have their own stack!
  - Values of local variable are not preserved when a thread is scheduled again ...
  - unless variables are declared `static` (on the heap)

A first Contiki program: Blink

- Same as our first TinyOS program
- Need to write a C source file with one process
  - Increase counter
  - Set LEDs accordingly
  - Sleep for one second

A first Contiki program: Blink

```
PROCESS(blink_process, "Blink!");

AUTOSTART_PROCESSES(&blink_process);

PROCESS_THREAD(blink_process, ev, data) {
  PROCESS_BEGIN();
  static struct etimer et;
  static int counter = 0;

  while (true) {
    counter++;
    leds_red(counter & 1);
    leds_green(counter & 2);
    leds_blue(counter & 4);

    etimer_set(&et, CLOCK_SECOND);
    PROCESS_WAIT_EVENT_UNTIL(etimer_expired(&et));
  }
  PROCESS_END();
}
```

Declare our process

Start process on boot

Define the process

egins

W

EGIN()

Need a timer
and a counter

Increase counter
and set LEDs

Set the

Wait until timer
has expired

Every process ends
with PROCESS_END()

Blink: Creating and uploading the binary

- Again, virtual machine image has everything installed
- To compile run `make blink` in project directory
- Binary: 16778 bytes in ROM, 2881 bytes in RAM
  - TinyOS: 2108 bytes in ROM, 34 bytes in RAM
  - Many modules that our program doesn't use
  - Disable modules manually to strip down binary size
  - Contiki programs can be made (almost) as small as their TinyOS counterparts

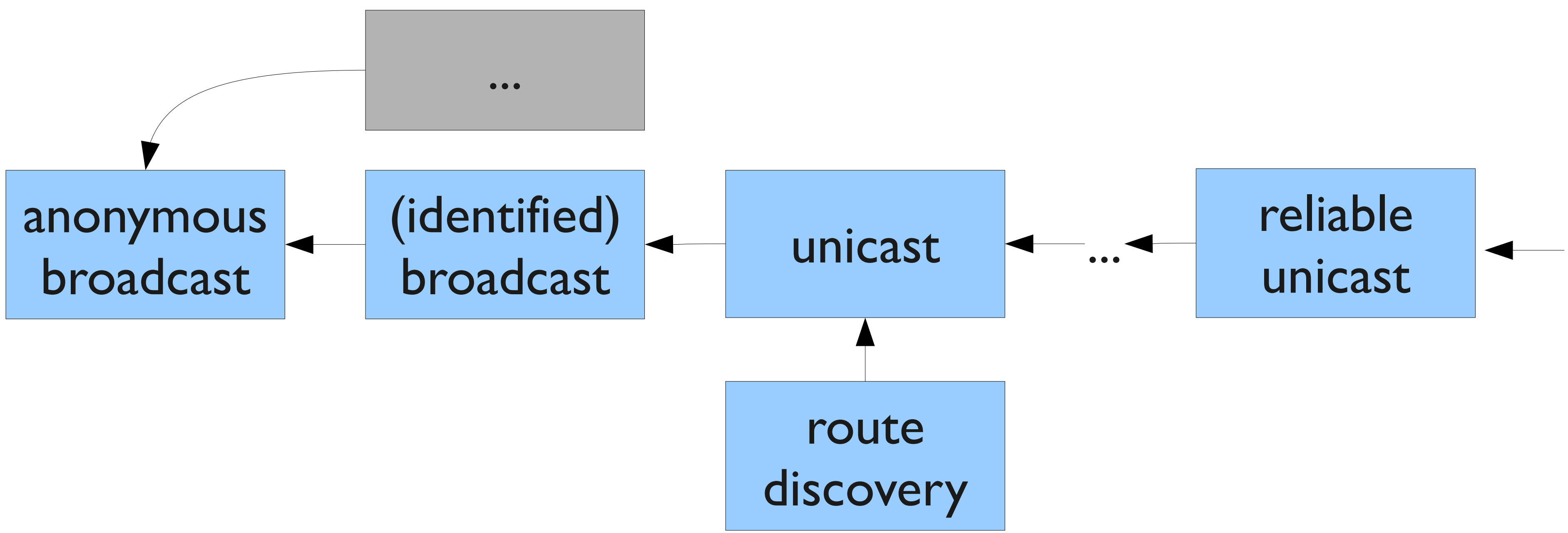
- To upload, run `make blink.upload`

Overview

- Sensor node hardware: Zolertia Z1
- TinyOS & nesC
  - Components & Interfaces
  - A first TinyOS program: Blink
  - Networking in TinyOS: Active messages
- Contiki
  - Protothreads
  - A first Contiki program: Blink
  - **Networking in Contiki: The Rime stack**
- Wrap-up

Networking in Contiki

- Contiki has multiple network stacks
  - IPv4 and IPv6, enables seamless Internet connectivity
  - Rime, a more "classical" sensor network stack
- Rime is a set of communication primitives that are built on top of each other



Rime: Packet buffer

- Packets are stored in the so-called packetbuf
- There is one single packetbuf

- Before sending, copy data to send into packetbuf
  - `packetbuf_copyfrom(data_to_send, length);`
  - This will copy **to** the packetbuf
- After receiving, copy data from packetbuf
  - `packetbuf_dataptr()` to get a pointer to the payload
  - Use `memcpy()` or the like to copy the data

Rime: Broadcast module

- Broadcast module offers single-hop, best-effort broadcast communication
  - Sender is identified (source address in every packet)
  - Representative for other Rime modules

- API
  - `broadcast_open(...)` - Initialize a broadcast handle
  - `broadcast_close(...)` - Close a broadcast handle
  - `broadcast_send(...)` - Send a packet

Rime: Broadcast module initialization

- Need to setup a handle before sending/receiving
- `broadcast_open(con, channel, callback)`
  - `con` – Handle to be created
  - `channel` – 16-bit integer for multiplexing
  - `callback` – Pointer to receive function

- A handle is also called a connection in Contiki
  - This is slightly misleading

Rime: Broadcast setup and receiving

- Set up handler and receive packets

```
void recv(struct broadcast_conn *, const rimeaddr_t);

struct broadcast_conn con;
struct broadcast_callbacks callba

PROCESS_THREAD(main_process, ev, data) {
  ...
  broadcast_open(&con, 1234, &callback);
  ...
}

void recv(struct broadcast_conn *con, const rimeaddr_t sender)
{
  uint16_t code;
  memcpy(&code, packetbuf_dataptr(), sizeof(code));

  if (code == 200) leds_on(LEDS_RED);
}
```

Declare a broadcast handle

nction to be receiving

Declare a broadcast

In the “main process” initialize the handle

Define the recv() function

Copy data from packetbuf e code

Turn on red LED if code is 200

Rime: Sending a broadcast packet

- Sending a packet is simple
  - Copy data to be sent to packetbuf
  - Call `broadcast_send(...)`

```
PROCESS_THREAD(main_process, ev, data) {
  ...
  broadcast_open(&con, 1234, &callback);
  ...
  static uint16_t code = 200;
  packetbuf_copyfrom(&code, sizeof(code));
  broadcast_send(&con);
  ...
}
```

- Usage of other Rime modules is similar

Wrap-up

- TinyOS and Contiki
  - Operating systems for resource-constrained, wireless devices
- Basic program structure
  - nesC modules, configurations and interfaces
  - Contiki Protothreads
- Basic networking
  - Active messages in TinyOS
  - Rime in Contiki

- Have a look at the code! Read more example code!

Advice for the labs & projects

- Programming embedded systems can be challenging
  - Little resources, no memory protection (in plain TinyOS, Contiki), debugging is hard ...
  - Can be a lot of fun, too :)

- Think before you start programming!
  - What are you going to do? How?
- Discuss with each other!
- Use on-line resources
  - Not only course page, but TinyOS/Contiki web site, Zolertia web site, mailing list ...

The end.

Enjoy the labs!