Contiki Crash Course

KTH, Stockholm, Sweden
9 October 2008

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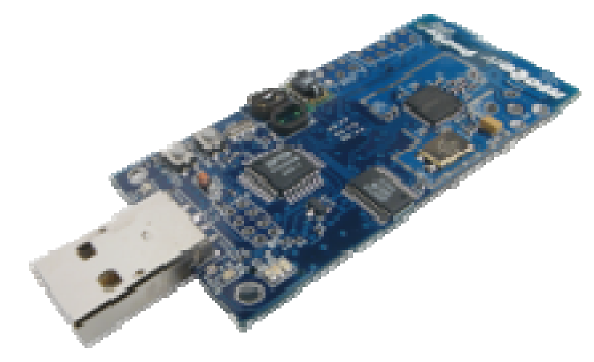
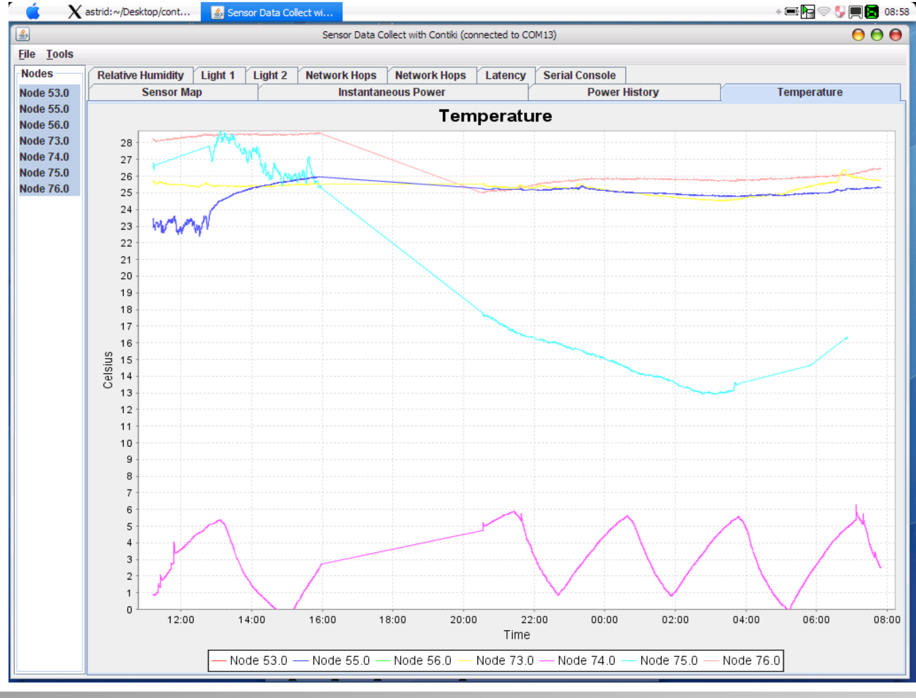
Purpose of today



- Understand Contiki
- Get started with Contiki
  - Programming
  - Hardware: Tmote Sky
  - Simulation in Cooja
- Hands-on experience
- Meet the people
- Get involved



Agenda

- 10:00 Introduction to Contiki programming
- 12:00 Lunch
- 13:00 Contiki for the Tmote Sky
- 14:00 Cooja: the Contiki simulator
  - Fredrik Österlind
- 15:00 End

People here today

- Adam Dunkels (Contiki author, project leader)
- Fredrik Österlind (Cooja author)

What is Contiki and where does it come from?

Contiki

- Contiki – pioneering open source operating system for sensor networks
  - IP networking
  - Hybrid threading model, protothreads
  - Dynamic loading
  - Power profiling
  - Network shell
- Small memory footprint
- Designed for portability
  - 14 platforms, 5 CPUs in current CVS code

Contiki as a tool

- For building systems
  - Programming abstractions
  - Shell
  - Power-saving mechanisms
- For writing papers
  - Power profiling

Contiki as knowledge transfer

- Making research useful
  - Transfer research results to useable C code
  - Promote simplicity and clarity over excessive complexity
  - Example: protothreads
- Put research into perspective
  - Transfer knowledge from practice to research
  - Example: IP for sensor networks

Pioneering, highly influential features of Contiki

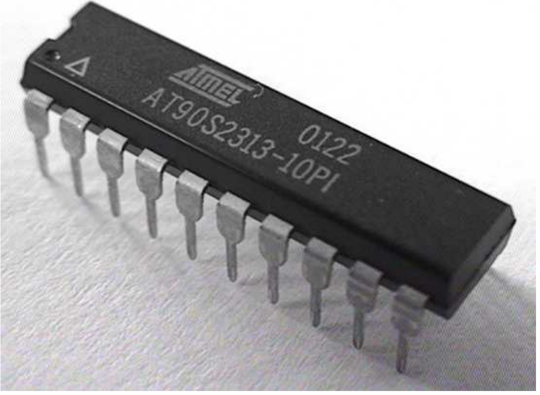
- Contiki: loadable modules [Emnets 2004]
  - SOS: loadable modules [MobiSys 2005]
- Contiki: preemptive threads on top of events [Emnets 2004]
  - TOSThreads: preemptive threads on top of events (TinyOS 2.1.0, 2008)
- Contiki: IP in sensor networks [EWSN 2004]
  - IETF 6lowpan: IP over 802.15.4 (2006)
  - IP for Smart Objects Alliance: IP in sensor networks (2008)
- Contiki: Software-based energy estimation (2007)
  - Quanto (OSDI 2008)

Prominent features, contd.

- Power profiling
  - Measure power consumption at the network scale
- Network shell
  - Makes interaction easier
- Rime stack
  - Makes network programming easier

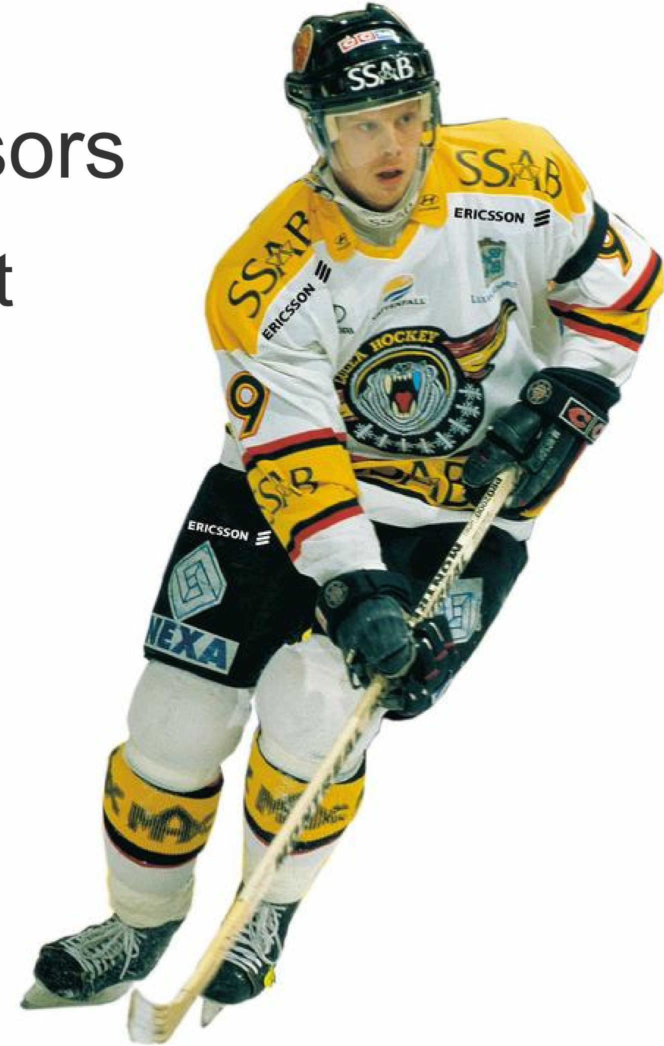
Contiki target systems

- Small embedded processors with networking
  - Sensor networks, smart objects, ...
- 98% of all microprocessors go into embedded systems
  - 50% of all processors are 8-bit
- MSP430, AVR, ARM7, 6502, ...

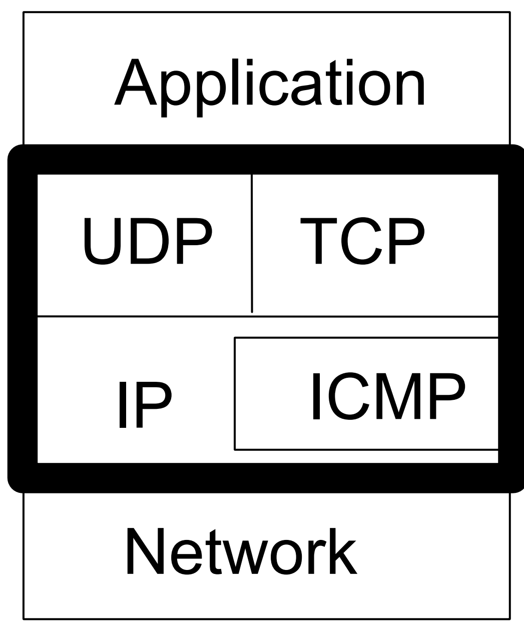


Background: The Arena Project (2000) LTU, Telia, Ericsson, SICS

- Hockey players with wireless sensors
  - Bluetooth sensors, camera on helmet
- Spectators with direct access to sensor readings
- TCP/IP used on the Bluetooth-equipped sensors
  - lwIP stack
- Luleå Hockey lost with 1-4...



Background: uIP – the world's smallest TCP/IP stack (2001)



- uIP – micro IP
- Open source
- ~5k code, ~2k RAM
  - Smallest configuration ~3k code, ~128 bytes RAM
- RFC compliant
  - Order of magnitude smaller than previous stacks
- Bottom-up design
  - Single-packet buffer
  - Event-driven API

lwIP and uIP today

- Very well-known in the embedded community
- Used in products from 100+ companies
- Covered in several books on embedded networking
- Porting uIP in professional magazines
- Recommended by leading professionals
- Competence specifically required in job postings

A few of the users (that I know of)

ABB
Actern
All Set
Altera
Amirix
Analog
Aurion
Axon D
BMW
Campb

Cisco Systems
Compendium Technologies

Engenium Tec

GE Security

NASA

Shift

Odense Unive
Denmark

Rowley Associates Ltd.

Contiki Timeline

- Contiki 2.2.1
- Contiki 2.2
- Instant Contiki
- Contiki 2.1
- Best demo @ SenSys 2007 (Mottola, Picco)!
- Power profiling [SenSys 2007]
- Rime [SenSys 2007]
- Power profiling [EmNets 2007]
- Contiki 2.0
- Dynamic linking [SenSys 2006]
- Protothreads paper [SenSys 2006]
- Cooja
- Protothreads
- Contiki paper [EmNets 2004]
- Contiki 1.2
- IP for Sensor networks [EWSN 2004]
- ESB port
- uIP paper [MobiSys 2003]
- Contiki 1.0
- uIP
- lwIP

2001 2002 2003 2004 2005 2006 2007 2008 2009

The name Contiki

- The Kon-Tiki raft: sailed across the Pacific Ocean with minimal resources

Demo: Contiki collect + shell

astrid:~/Desktop/cont... Sensor Data Collect wi... 08:58

Sensor Data Collect with Contiki (connected to COM13)

File Tools

Nodes

Node 53.0
Node 55.0
Node 56.0
Node 73.0
Node 74.0
Node 75.0
Node 76.0

Relative Humidity | Light 1 | Light 2 | Network Hops | Network Hops | Latency | Serial Console

Sensor Map | Instantaneous Power | Power History | Temperature

Temperature

Celsius

28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0

12:00 14:00 16:00 18:00 20:00 22:00 00:00 02:00 04:00 06:00 08:00

Time

Node 53.0 — Node 55.0 — Node 56.0 — Node 73.0 — Node 74.0 — Node 75.0 — Node 76.0

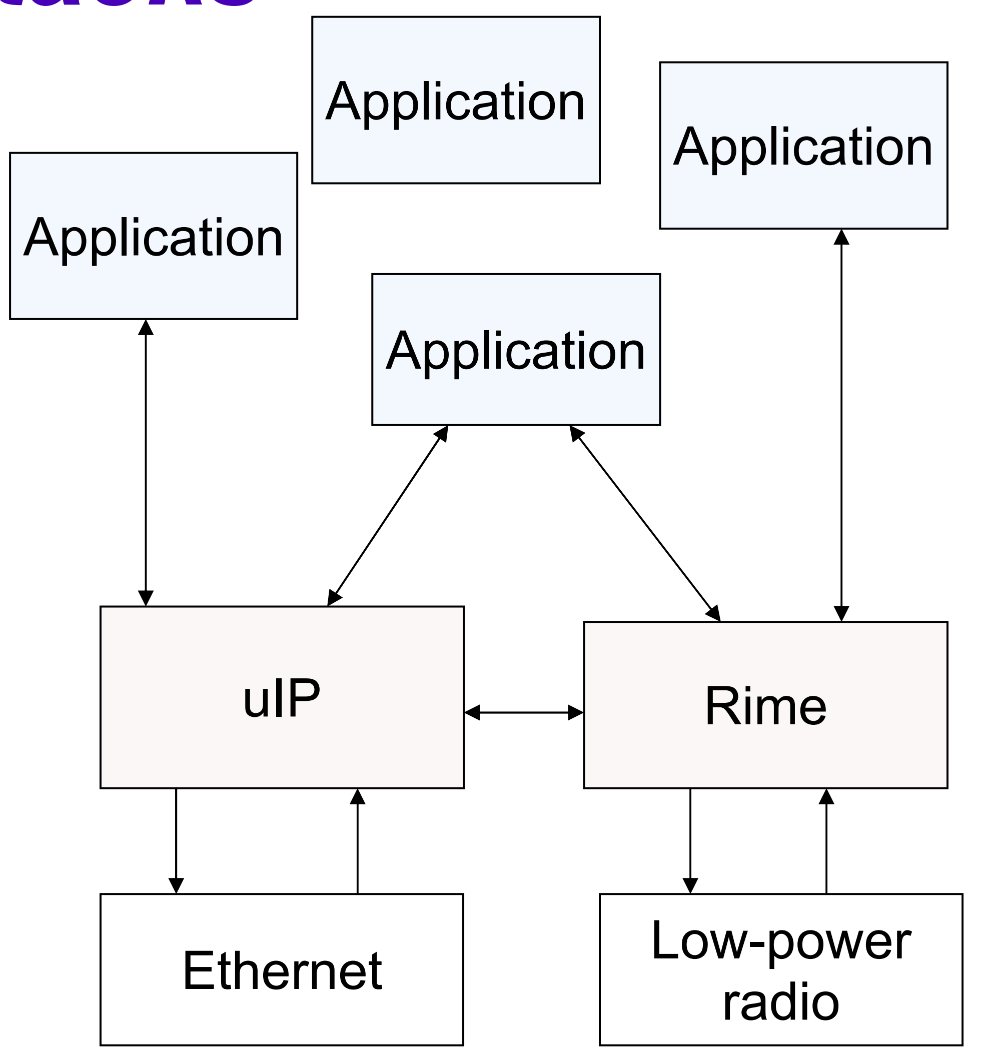
The shell

- Command-line interaction with a network of Contiki nodes
- Unix-style pipelines
- File system interaction: ls, write, read
- Repetition: repeat, randwait
- Network commands: netcmd
- `sense | senseconv`
- `sense | write file | send`
- `repeat 0 20 { randwait 20 { sense | blink | send } } &`
- `collect | binprint &`

Communication in Contiki

Contiki: two communication stacks

- Two communication stacks in Contiki
  - uIP – TCP/IP
  - Rime – low overhead
- Applications can use either or both
  - Or none
- uIP can run over Rime
- Rime can run over uIP



uIP

- Processes open TCP or UDP connections
  - tcp_connect(), tcp_listen(), udp_new()
- **`tcpip_event`** posted when new connection arrives, new data arrives, connection is closed, etc.
- Reply packet is sent when process returns
- TCP connections periodically polled for data
- UDP packets sent with uip_udp_packet_send()

uIP APIs

- Two APIs
  - The “raw” uIP event-driven API
  - Protosockets – sockets-like programming based on protothreads
- Event-driven API works well for small programs
  - Explicit state machines
- Protosockets work better for larger programs
  - Sequential code

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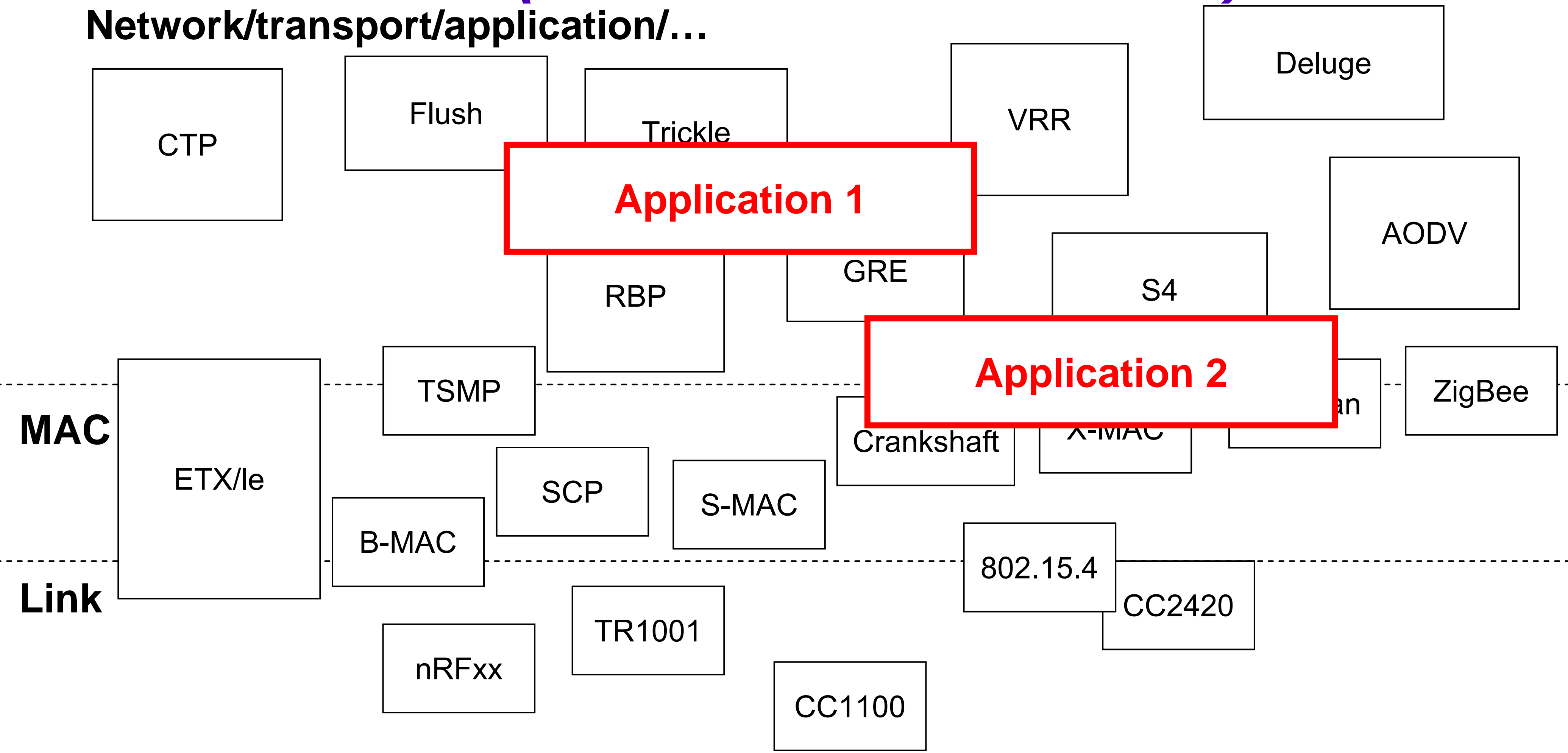
Protosockets: example

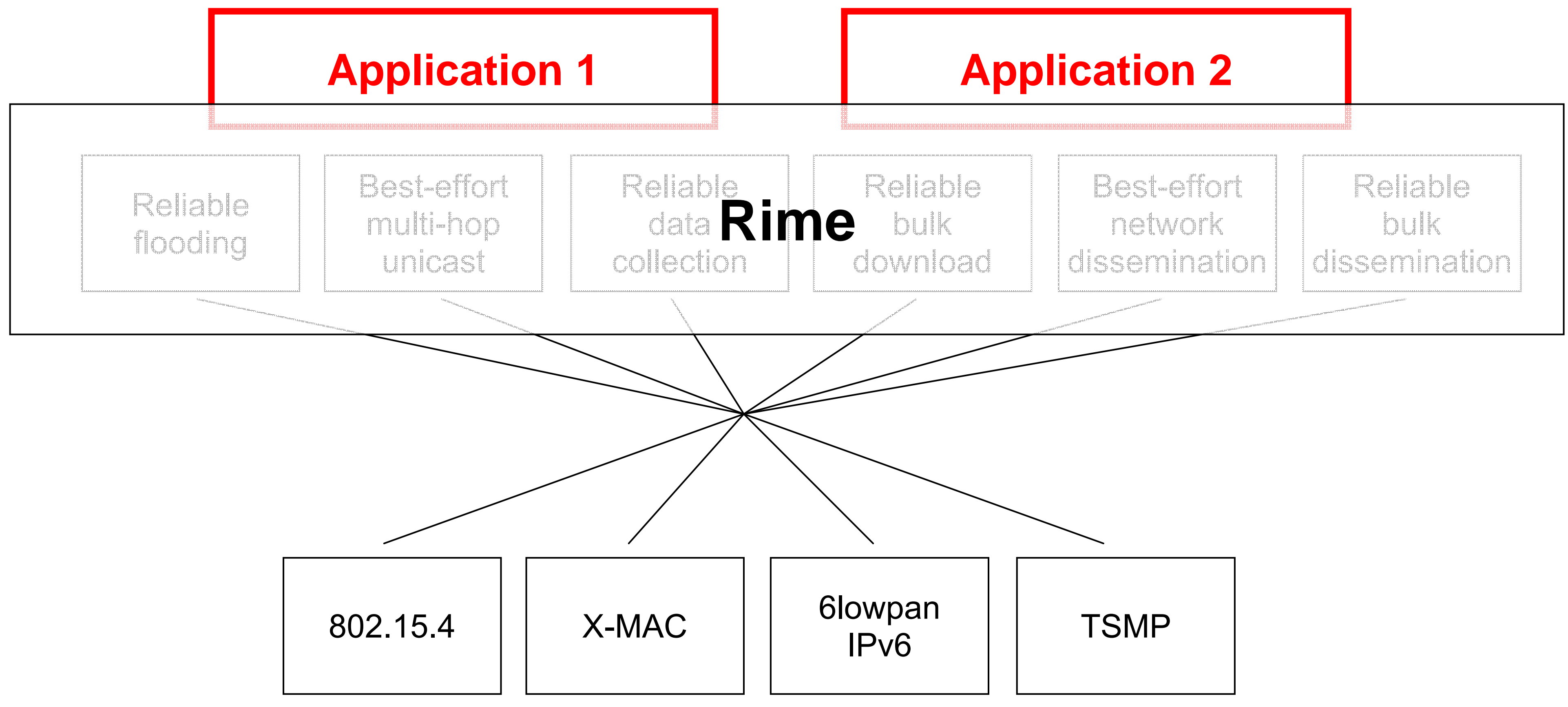
```
Int smtp_protothread(struct psock *s)
{
  PSOCK_BEGIN(s);

  PSOCK_READTO(s, '\n');

  if(strncmp(inputbuffer, "220", 3) != 0) {
    PSOCK_CLOSE(s);
    PSOCK_EXIT(s);
  }

  PSOCK_SEND(s, "HELO ", 5);
  PSOCK_SEND(s, hostname, strlen(hostname));
  PSOCK_SEND(s, "\r\n", 2);

  PSOCK_READTO(s, '\n');

  if(inputbuffer[0] != '2') {
    PSOCK_CLOSE(s);
    PSOCK_EXIT(s);
  }
```

Rime

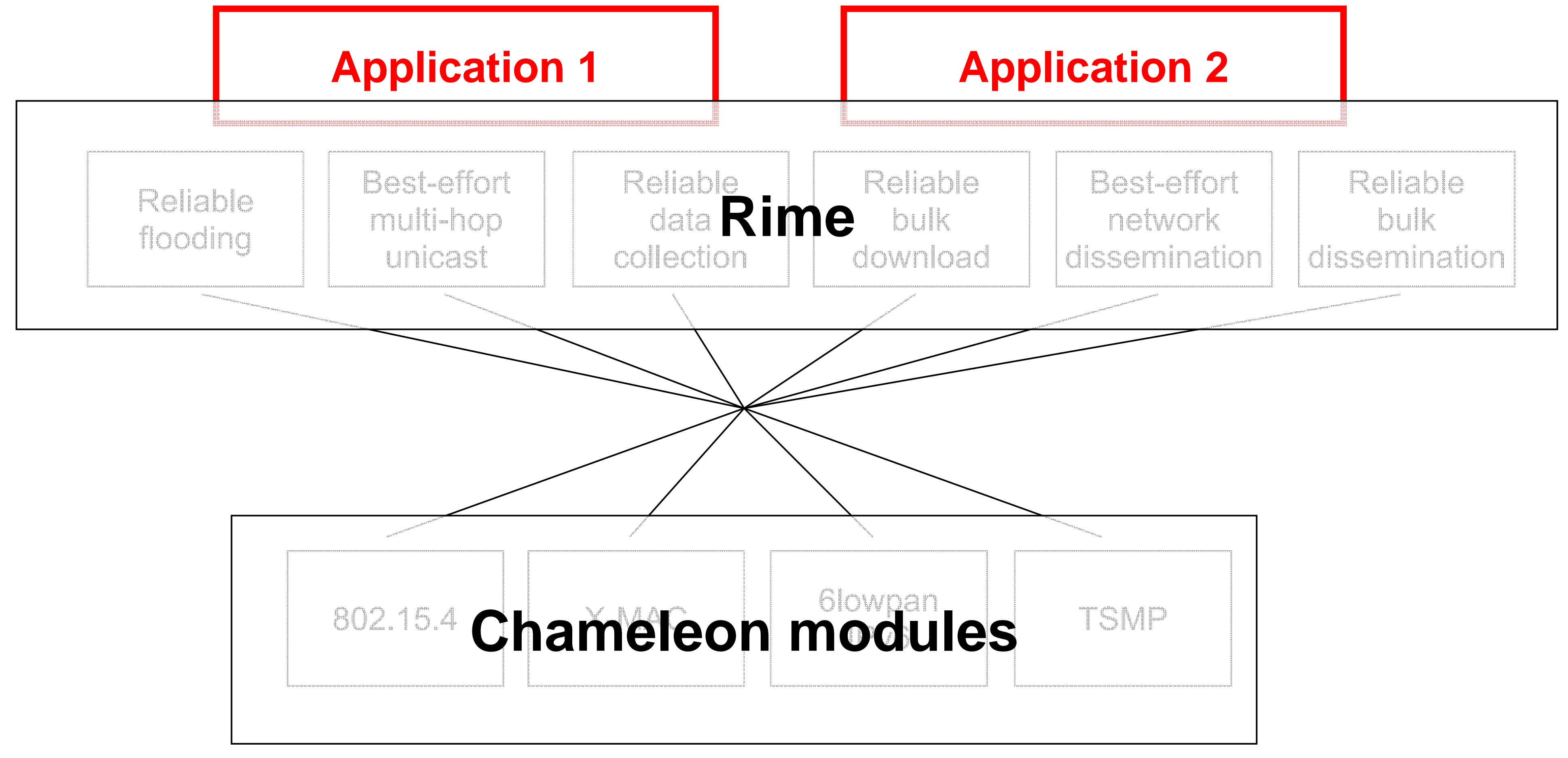
Sensor communication programming (before Contiki/Rime)



Rime: “sockets” for sensor networks



Chameleon: adapting to underlying MAC layers, link layers, protocols



Chameleon / Rime

- Separating packet headers from protocol logic
- Rime: a set of communication primitives
  - Lightweight layering: primitives built in terms of each other
  - Compose simple abstractions to more complex ones
- Chameleon modules
  - Header construction/parsing done separate from communication stack

Chameleon / Rime

Application 1

Application data
All packet attributes

Application 2

Application 3

Deal with communication here

Data collection protocol

Separating packet headers from protocol logic

Application data
Packet attributes

Application data
All packet attributes

More packet a

Chameleon

Confine bit-level headaches here

802.15.4

IP

Bit-packet header

…

A Communication Protocol with Different Radios

Low-level radio (cc1100)

Local source
Final destination
Original sender

- No extra headers added by radio

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Header Fields hold the Same Information

Low-level radio (cc1100) ←→ 802.15.4 radio (cc2420)

Low-level radio (cc1100)
Local source
Final destination
Original sender

802.15.4 radio (cc2420)	
Length	FC0
FC1	Seqno
PAN ID	
Destination address	
Sender address	
Local source	
Final destination	
Original sender	

Chameleon: Efficient Header Compression

Byte-level radio (cc1100) ⟷ 802.15.4 radio (cc2420) ⟷ IP over 802.15.4

Byte-level radio (cc1100)
Local source
Final destination

802.15.4 radio (cc2420)	
Length	FC0
FC1	Seqno
PAN ID	
Sender address	
Local source	
Final destination	
Original sender	

IP over 802.15.4
802.15.4 header
802.15.4 src address
IP hdr (compressed)
IP src address
Local source
Final destination
Original sender

Separating packet headers from protocol logic

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Rime – a lightweight, layered communications stack

- A set of communication abstractions (in increasing complexity):
  - Single-hop broadcast (broadcast)
  - Single-hop unicast (unicast)
  - Reliable single-hop unicast (runicast)
  - Best-effort multi-hop unicast (multihop)
  - Hop-by-hop reliable multi-hop unicast (rmh)
  - Best-effort multi-hop flooding (netflood)
  - Reliable multi-hop flooding (trickle)

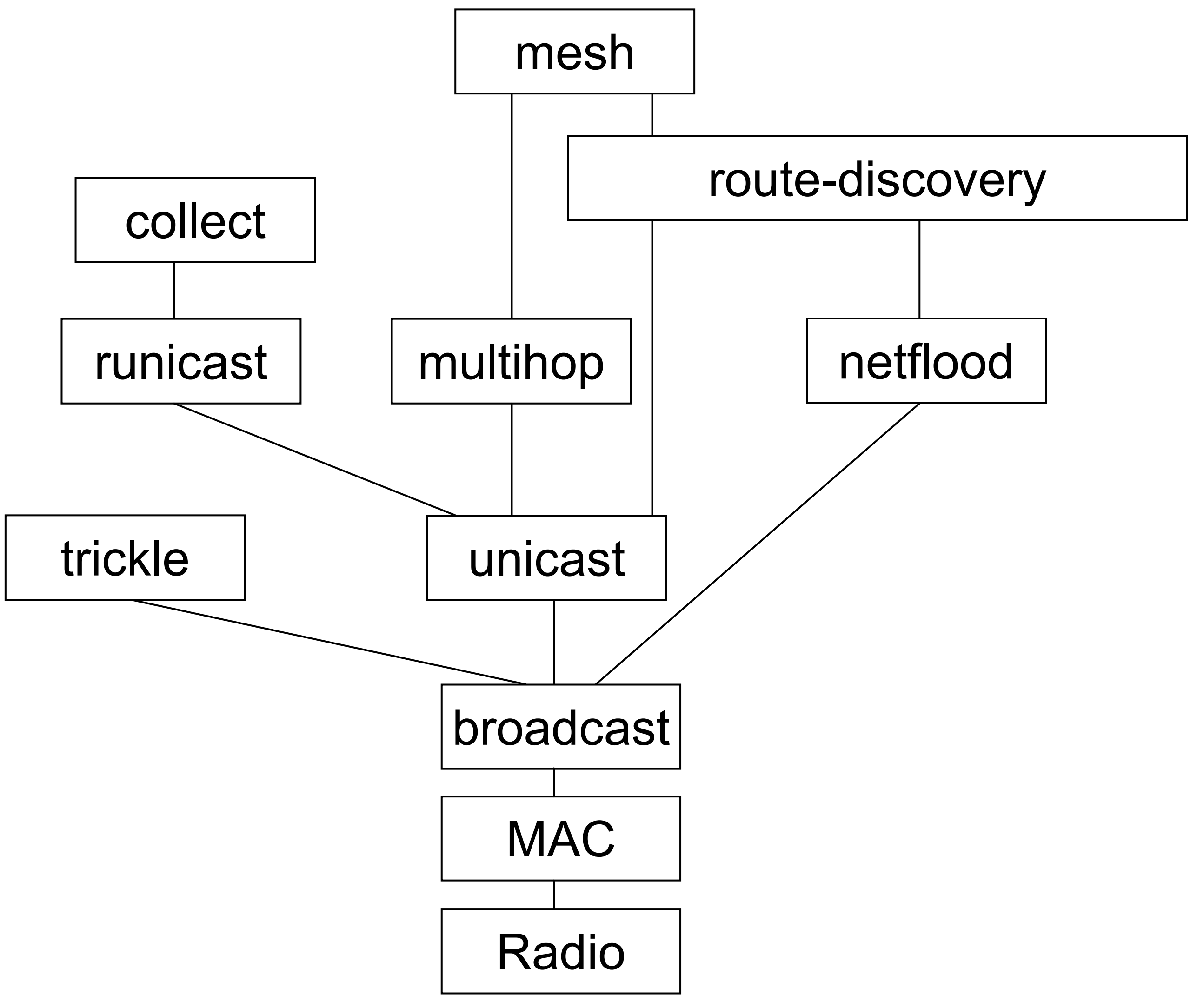
Rime – a lightweight, layered communications stack

- A set of communication abstractions (continued)
  - Hop-by-hop reliable data collection tree routing (collect)
  - Hop-by-hop reliable mesh routing (mesh)
  - Best-effort route discovery (route-disovery)
  - Single-hop reliable bulk transfer (rudolph0)
  - Multi-hop reliable bulk transfer (rudolph1)

Rime – layers reduce complexity

- Each module is fairly simple
  - Compiled code between 114 and 598 bytes
- Complexity handled through layering
  - Modules are implemented in terms of each other
- Not a fully modular framework
  - Full modularity typically gets very complex
  - Instead, Rime uses strict layering

Rime map (partial)



Rime – the name

- **Rime frost** composed of many thin layers of ice
- **Syllable rime** – last part of a syllable
  - Communication formed by putting many together

Rime channels

- All communication in Rime is identified by a 16-bit channel
- Communicating nodes must agree on what modules to use on a certain channel
  - Example
    - unicast <-> unicast on channel 155
    - netflood <-> netflood on channel 130
- Channel numbers < 128 are reserved by the system
  - Used by the shell, other system apps

Rime programming model

- Callbacks
  - Called when packet arrives, times out, error condition, …
- Connections must be opened before use
  - Arguments: module structure, channel, callbacks

Rime example: send message to all neighbors

```
void recv(struct broadcast_conn *c) {   /* Called when a */
  printf("Message received\n");         /* message is    */
}                                       /* received.     */

struct broadcast_callbacks cb = {recv};/* Callback */
struct broadcast_conn c;                /* Connection */

void setup_sending_a_message_to_all_neighbors(void) {
  broadcast_open(&c, 128, &cb);         /* Channel 128 */
}

void send_message_to_neighbors(char *msg, int len) {
  rimebuf_copyfrom(msg, len);           /* Setup rimebuf */
  broadcast_send(&c);                   /* Send message  */
}
```

Receive data

Open connection

Send data

Rime example: send message to entire network

```
void recv(struct trickle_conn *c) {/* Called when a*/
  printf("Message received\n");    /* message is     */
}                                  /* received.      */

struct trickle_callbacks cb = {recv}; /* Callbacks */
struct trickle_conn c;             /* Connection     */

void setup_sending_a_message_to_network(void) {
  trickle_open(&c, CLOCK_SECOND, 129, &cb);
                                   /* Channel 128    */
}

void send_message_to_network(char *msg, int len) {
  rimebuf_copyfrom(msg, len);      /* Setup rimebuf */
  trickle_send(&c);                /* Send    */
}
```

Rime example: send message to node somewhere in the network

```
void recv(struct mesh_conn *c, rimeaddr_t *from) {
  printf("Message received\n");
}

struct mesh_callbacks cb = {recv, NULL, NULL};
struct mesh_conn c;

void setup_sending_a_message_to_node(void) {
  mesh_open(&c, 130, &cb);
}

void send_message_to_node(rimeaddr_t *node, char *msg,
                          int len) {
  rimebuf_copyfrom(msg, len);
  mesh_send(&c, node);
}
```

Structure of the Rime stack

Layer	Location
Application	apps/shell, …
Rime + Chameleon	
Power-saving MAC	core/net/mac/
Radio	CC2420

Writing a MAC protocol

- core/net/mac/nullmac.c
  - Simplest MAC protocol (always on)
- core/net/mac/lpp.c
  - Simple power-saving MAC protocol [IPSN 2007]
- core/net/mac/xmac.c
  - More complex power-saving MAC protocol [SenSys 2006]

Writing a radio driver

- core/dev/cc2420.c

Summary so far

- Communication: uIP and Rime
  - uIP: TCP/IP
  - Rime: low-power, routing
  - Can run on top of each other

Programming in Contiki

Overview

- Hello, world!
- Contiki processes and protothreads
- Timers in Contiki
- The Contiki build system
- Developing software with Contiki
  - Native port
- Directory structure
- Coding and naming standards

Hello, world!

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

/* Define the process code */
PROCESS_THREAD(hello_world_process, ev, data) {
  PROCESS_BEGIN();              /* Must always come first */
  printf("Hello, world!\n");   /* Initialization code goes here */
  while(1) {                    /* Loop for ever */
    PROCESS_WAIT_EVENT();       /* Wait for something to happen */
  }
  PROCESS_END();                /* Must always come last */
}
```

Contiki processes and protothreads

Contiki processes

- The Contiki kernel is event-based
  - Invokes processes whenever something happens
    - Sensor events, processes starting, exiting
  - Process invocations must not block
- Protothreads provide sequential flow of control in Contiki processes

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The event-driven Contiki kernel

- Event-driven vs multithreaded
  - Event-driven requires less memory
  - Multithreading requires per-thread stacks

Threads require per-thread stack memory

- Four threads, each with its own stack

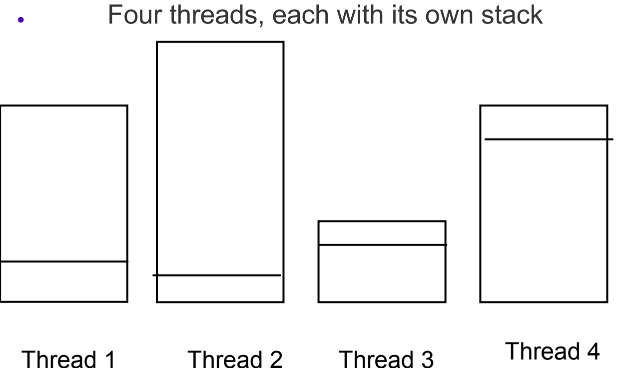
Thread 1

Thread 2

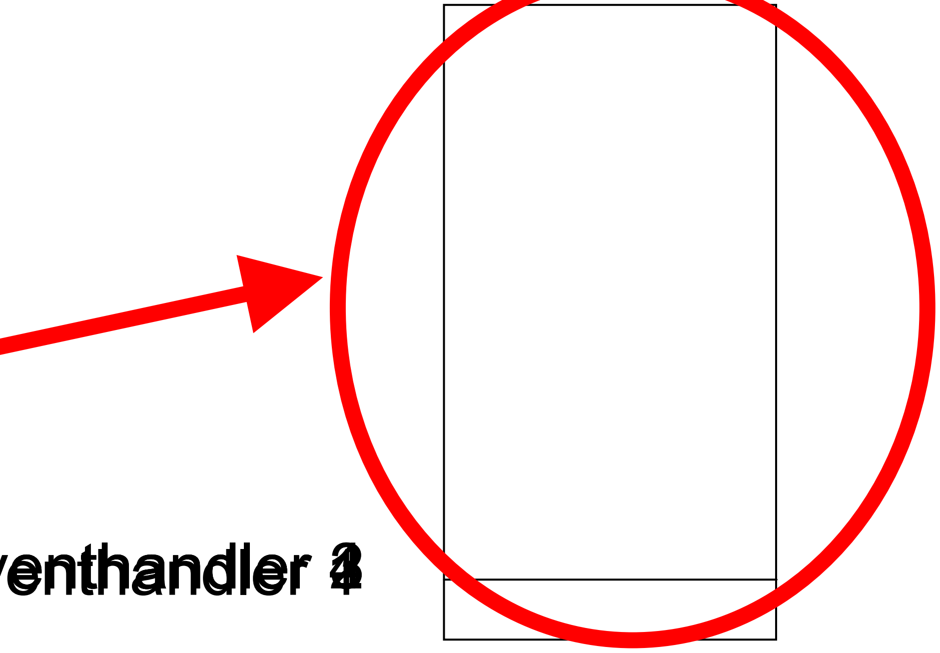
Thread 3

Thread 4

Events require one stack



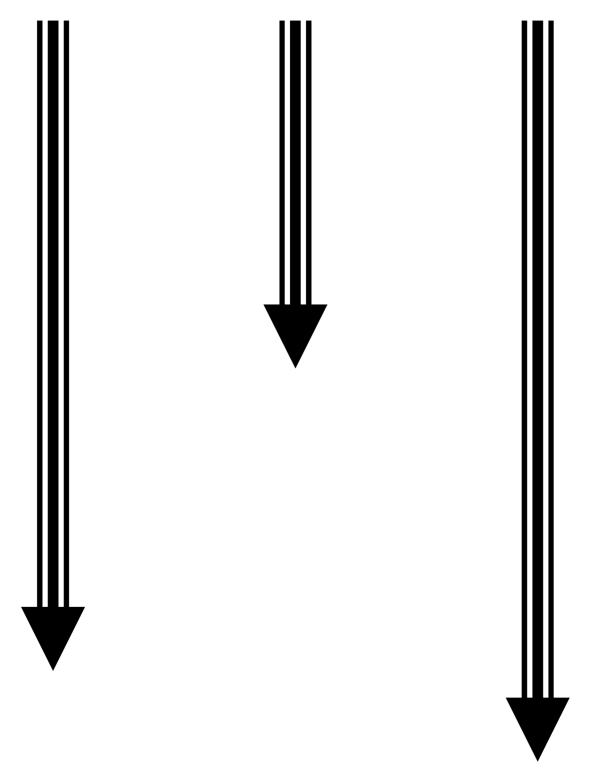
- Four event handlers, one stack



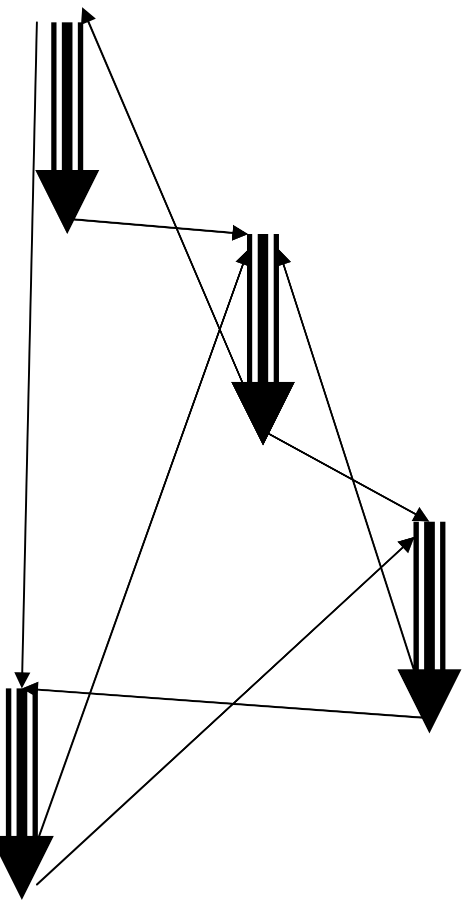
Stack is reused for every event handler

The problem with events: code flow

Threads: sequential code flow



Events: unstructured code flow



Very much like programming with GOTOs

Contiki: Combining event-driven and threads

- Event-based kernel
  - Low memory usage
  - Single stack
- Multi-threading as a library (mt_*)
  - For those applications that needs it
  - One extra thread, one extra stack
- The first system in the sensor network community to do this

However...

- Threads still require stack memory
- Unused stack space wastes memory
  - 200 bytes out of 2048 bytes is a lot!
- A multi-threading library quite difficult to port
  - Requires use of assembly language
  - Hardware specific
  - Platform specific
  - Compiler specific

Protothreads: A new programming abstraction

- A design point between events and threads
- Programming primitive: conditional blocking wait
  - PT_WAIT_UNTIL(*condition*)
- Single stack
  - Low memory usage, just like events
- Sequential flow of control
  - No explicit state machine, just like threads
  - Programming language helps us: **if** and **while**

An example protothread

```
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 require only one stack

Threads require per-thread stack memory

- Four threads, each with its own stack

Thread 1 Thread 2 Thread 3 Thread 4

Just like events

Events require one stack

- Four event handlers, one stack

- Four protothreads, one stack

Protothread 4

Contiki processes are protothreads

```
PROCESS_THREAD(hello_world_process, ev, data) {
  PROCESS_BEGIN();
  printf("Hello, world!\n");
  while(1) {
    PROCESS_WAIT_EVENT();
  }
  PROCESS_END();
}
```

Limitations of the protothread implementation

- Beware!
- Automatic variables not stored across a blocking wait
  - Compiler does produce a warning
  - Workaround: use static local variables instead
- Constraints on the use of switch() constructs in programs
  - No warning produced by the compiler
  - Workaround: don’t use switches
- Beware!

Two ways to make a process run

- Post an event
  - process_post(process_ptr, eventno, ptr);
    - Process will be invoked later
  - process_post_synch(process_ptr, eventno, ptr);
    - Process will be invoked now
  - Must **not** be called from an interrupt (device driver)
- Poll the process
  - process_poll(process_ptr);
  - Sends a PROCESS_EVENT_POLL event to the process
  - Can be called from an interrupt

Timers in Contiki

Four types of timers

- 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
  - Used by Rime
- struct rtimer
  - Real-time timer, calls a function at an exact time

Using etimers in processes

```
PROCESS_THREAD(hello_world_process, ev, data) {
  static struct etimer et;          /* Must be static      */
  PROCESS_BEGIN();                  /* since processes are */
                                    /* protothreads        */
  while(1) {
    /* Using a struct timer would not work, since
       the process would not be invoked when it expires. */
    etimer_set(&et, CLOCK_SECOND);
    PROCESS_WAIT_EVENT_UNTIL(etimer_expired(&et));
  }
  PROCESS_END();
}
```

The Contiki build system

The Contiki build system

- Purpose 1: easy to recompile applications for different platforms
- Purpose 2: keep application code out of the Contiki directories
- Only need to change the make command to build for different platforms
- Ideally, no changes needed to the programs
  - In practice, not all ports support everything
  - Particularly low-level hardware stuff

Example: building hello world

Command	Description
cd examples/hello-world	
make TARGET=native	Build monolithic system for native
./hello-world.native	Run entire Contiki system + app
make TARGET=netsim	Build netsim simulation
./hello-world.netsim	Run netsim simulation
make TARGET=sky	Build monolithic system image
make TARGET=sky hello-world.u	Build & upload system image
make TARGET=sky hello-world.ce	Build loadable module
make TARGET=esb	Monolithic system image for ESB
make TARGET=esb hello-world.u	Build & upload image
make TARGET=esb hello-world.ce	Build loadable module

make TARGET=

- TARGET=name of a directory under platform/
- make TARGET=xxx savetarget
  - Remembers the TARGET
  - Example: make TARGET=netsim savetarget

Developing software with Contiki

Developing software with Contiki

- The first rule of software development with Contiki:
  - Don’t develop in the target system!
    - Unless you are writing really, really low-level code
  - Do as much as possible in simulation first
    - Contiki helps you a lot
    - Native, netsim, minimal-net ports, Cooja
  - Much easier and less tedious to debug code in simulation
    - Also allows you to see global behavior

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Developing software with Contiki

- The second rule of software development with Contiki:
  - Keep your code in a separate project directory
  - Helps keep application code separate from the Contiki source code
    - If you need to change the Contiki source code, make a separate copy of the file in the project directory
    - Local files override Contiki files
  - Simple Makefile in project directory

Makefile in project directory

```
CONTIKI = (path to Contiki directory)
all: name-of-project-file-without-extension
include $(CONTIKI)/Makefile.include
```

examples/hello-world/Makefile

```
CONTIKI = ../..
all: hello-world
include $(CONTIKI)/Makefile.include
```

Suggested work plan for developing Contiki code

1. Play around with the target hardware
   - Purpose: get to know the hardware
   - Write small programs that blink LEDs, produce output
2. Put the target hardware away
3. Develop the application logic in simulation
   - Test the application in simulation
4. Recompile for the target hardware
   - Test application on the target hardware
   - Fix bugs and finish up on target hardware

Case study: rewrite xmac.c

- cd examples
- mkdir new-xmac
- cd new-xmac
- cp ../sky-shell/* .
- cp ../../core/net/mac/xmac.c .
- make sky-shell.upload
- make login [run application]
- [edit xmac.c, repeat make sky-shell.upload]

Contiki directory structure

apps/ – architecture independent applications

One subdirectory per application

core/ – system source code

Subdirectories for different parts of the system

cpu/ – CPU-specific code

One subdirectory per CPU

doc/ – documentation

examples/ – example project directories

Subdirectories with project

platform/ – platform-specific code

One subdirectory per platform

tools/ – software for building Contiki, sending files

Coding and naming standards

Coding and naming standard

- Important for keeping the project consistent
- When writing code that might end up in Contiki, use the Contiki coding standard from the start
  - Harder to change the look afterwards

Names in Contiki

- In Contiki, all names are prefixed with the module name
  - process_start(), rime_init(), clock_time(), memb_alloc(), list_add()
- Prefix makes it possible to mentally locate all function calls
- All code must abide by this
  - There are a few exceptions in the current code, but those are to be removed in the future

What to avoid

- noCamelCase()
- No_Capital_Letters()
  - #define EXCEPT_FOR_MACROS()

File names

- Contiki uses hyphenated-file-names rather than underscores_in_file_names

Code style

- doc/code-style.c

```
/*---------------------------------------------------------*/
void
code_style_example_function(void)
{
  for(i = 0; i < 10; ++i) {
    if(i == c) {
      return c;
    }
  }
}
/*---------------------------------------------------------*/
```

In summary

- Processes and protothreads
  - Process run when events are posted
- Timers: etimers for processes
- The build system: app code separate
- Developing software for Contiki: don't develop in the target system
- Keep naming and style consistent

Get involved!

- Write great papers where you use Contiki
  - SenSys, IPSN, SPOTS, OSDI, NSDI, SIGCOMM, Usenix, HotNets, RealWSN, EWSN, HotEmnets
- Write great papers where you improve Contiki
  - And outperform other systems
- Actively advocate Contiki in forums, mailing lists, conferences

Getting code into Contiki

- We are very happy to receive bugfixes, comments!
- Code must
  - Work
  - Be of high quality
  - Follow the naming style
  - Follow the code style (exactly)

Contiki project structure

- Contiki is a meritocracy
- Core group
  - Adam Dunkels, Oliver Schmidt, Fredrik Österlind, Niclas Finne, Joakim Eriksson, Nicolas Tsiftes, Takahide Matsutsuka
- Developers
  - Zhitao He, Simon Barner, Simon Berg
  - 5+ incoming
- Contributors
  - Thiemo Voigt, Björn Grönvall, Tony Nordström, Matthias Bergvall, Groepaz, Ullrich von Bassewitz, Lawrence Chitty, Fabio Fumi. Matthias Domin, Christian Groessler, Anders Carlsson, Mikael Backlund, James Dessart, Chris Morse

Conclusions

- Contiki – a pioneering OS for sensor networks
  - Makes research useful
  - Simplicity and clarity instead of excessive complexity
- Communication with uIP and Rime
- Programming with protothreads and processes
- Help Contiki by writing great papers
  - Publish at high-impact venues!

Thank you

http://www.sics.se/contiki/

Contiki

A Memory-Efficient Operating System for Embedded Smart Objects

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New Industry Alliance Promotes the use of IP in Networks of Smart Objects

News

Written by Adam Dunkels, Tuesday, 16 September 2008

Cisco, SAP and Sun Among 25 Charter Members of the IPSO Alliance
Offering Education, Interoperability Testing for Embedded IP Applications

SAN FRANCISCO, Calif., Sept. 16, 2008 – A group of leading technology vendors and users have formed the IP for Smart Objects (IPSO) Alliance, whose goal is promoting the Internet Protocol (IP) as the networking technology best suited for connecting sensor- and actuator-equipped or "smart" objects and delivering information gathered by those objects.

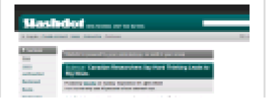
Read more...

Slashdot: "IP Meets Physical Reality", article about Contiki

News

Written by Adam Dunkels, Sunday, 07 September 2008

It was a while since Contiki was mentioned over at Slashdot, but this



Wireless Sensor Networking in 2000: The Arena Project

Perspective

Written by Adam Dunkels, Saturday, 06 September 2008

After the release of Contiki 2.2.1, we take a look at the

Current Events

Contiki 2.2.1 Released

We are happy to announce the release of Contiki 2.2.1! The focus of this release is to fix bugs found in the 2.2 version. The changes are: significant bugfixes and performance improvements to the data collection protocol; improved data presentation in the Contiki collect program; reduction in power consumption for the X-MAC radio mechanism; performance improvements and bugfixes to the Coffee flash file system; workaround for a problem with the CC2420 radio.

Download here. Changelog here.

Recent Popular Articles

- Contiki 2.2.1 Released
- The Instant Contiki Development Environment 1.0a

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