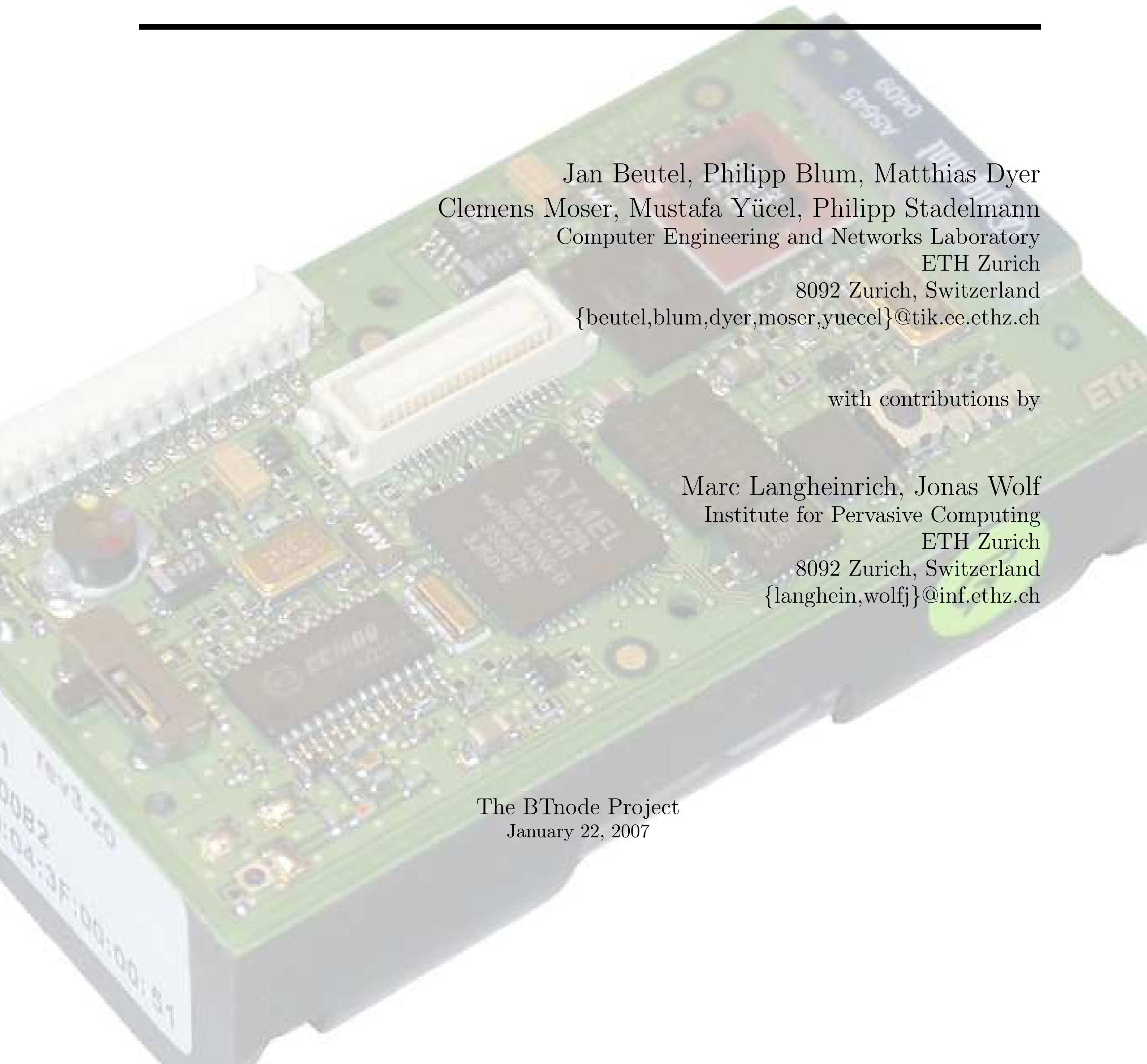

BTnode Programming — An Introduction to BTnut Applications

Number 1.5

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The BTnode Project
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Contents

Date	**Section**	**Who**	**Changes**
Mar 2, 2005		jb	Initial Version 0.1
Mar 24, 2005	2, 3	jb, pb	Initial drafts of 2st and 2nd exercise done
Mar 30, 2005	3	jb	Added input from beta-testers, ready for distribution
May 10, 2005	1, 6	jb, cm	Edits after Clemens first import, added BTnode developer kit to introduction
May 12, 2005	all	jb, cm, md	Fixed graphics and rest of 5 and 6, prep for first release
Mar 21, 2006	1	jb	Minor updates
Mar 24, 2006	1,2,appendix	jb	Finished chapter 1 and 2 draft for SS2006
Apr 5, 2006	2	jw	Added bootloader
Apr 5, 2006	1,2,4,appendix	jb	Minor changes to chapter 2. Checked all solutions and moved some files around
Apr 6, 2006	1	ml	Added Marc's superb introduction modification
Apr 19, 2006	2	jb	Replaced 115200 by 57600 (default baudrate)
May 29, 2006	6	jb, cm	Bluetooth updates for 2006, created version 1.3
Nov 13, 2006	7	my	Added chapter 7
Jan 08, 2007	9,10	jb	Added chapters 9 & 10 by Marc Langheinrich
Jan 15, 2007	all	jb	Added tutorial overview and changed solution numbering
Jan 17, 2007	all	my	complete review with minor changes
Jan 22, 2007			Version 1.5

Table 1: Revision History

Chapter 1

Introduction

1.1 The BTnodes and the BTnut System Software

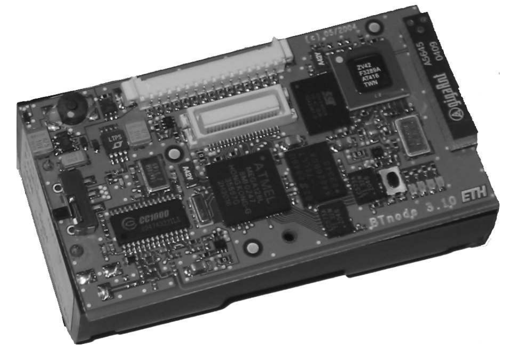


Figure 1.1: The BTnode rev3.

The *BTnode* is an autonomous wireless communication and computing platform based on a Bluetooth radio and a microcontroller [3]. It serves as a demonstration platform for research in mobile and ad-hoc connected networks (MANETs) and distributed sensor networks. The BTnode has been jointly developed at ETH Zurich by the Computer Engineering and Networks Laboratory (TIK) and the Research Group for Distributed Systems. Currently, the BTnode is primarily used in the NCCR-MICS research projects.

In addition to its Bluetooth radio, the latest BTnode revision (rev3) [2] also features a low-power radio identical to the one used on the Crossbow/Berkeley Mica2 Motes [8], allowing it to interact with both Mica2-based nodes and previous, Bluetooth-only revisions of the BTnode. Both radios can be operated simultaneously or be independently powered off completely when not in use, considerably reducing the idle power consumption of the device.

BTnodes run an embedded systems OS from the open source domain, called Nut/OS. Nut/OS is designed for the Atmel ATmega128 microcontroller (which is used on the BTnodes) and intentionally kept very simple. According to the Nut/OS description, it features:

- Non preemptive cooperative multi-threading
- Events
- Periodic and one-shot timers
- Dynamic heap memory allocation
- Interrupt driven streaming I/O

In order to use Nut/OS on the BTnodes, a set of BTnode-specific drivers have been added, and in particular a Bluetooth stack for its on-board Bluetooth radio. These three pieces form together the *BTnut system software* or short BTnut.

In this tutorial, we will learn how to use the BTnut system software to deploy sensor node applications on the BTnode wireless sensor node platform.

1.2 Intended Audience

This tutorial originated in the Embedded Systems lecture, a graduate course taught at the Department of Information Technology and Electrical Engineering, ETH Zurich and a graduate course on Wireless Sensor Network taught at the Department of Computer Science, ETH Zurich. It requires basic knowledge of C-programming and embedded systems and should give an overview of the capabilities of networked embedded systems and their key properties. However, apart from its usage in the lecture, this tutorial provides a basic introduction to programming on the BTnode platform, so it should also be beneficial to the occassional computer scientist not versed in all things electrical.

Each chapter comes with a set of exercises that are supposed to get you accustomed to basic, everyday tasks of an embedded engineer. The order in which the exercises are performed is not of crucial importance, and whole chapters can be left out to suit the individual needs (e.g., computer scientists might want to skip those concerning hardware issues). However, we suggest that you perform the exercises in the order given to minimize unforeseen complications.

1.3 Hard- and Software Requirements

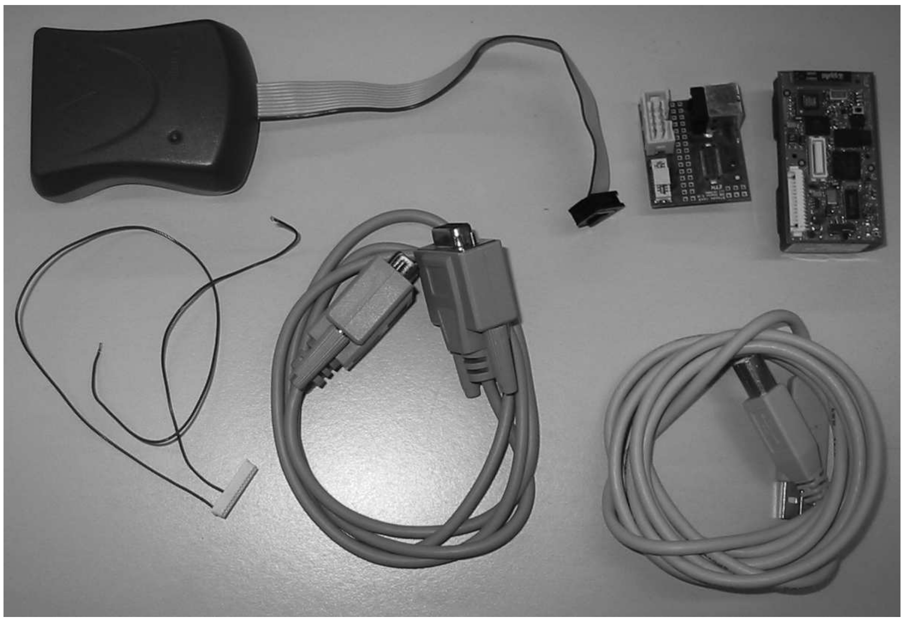


Figure 1.2: The BTnode development kit. The minimal set of tools consists of the three items on the very right: a BTnode, a USB programming board, and a USB cable. Additionally, some exercises require the use of an ISP programmer, a serial cable, and a 15-Pin Molex breakout cable (left half).

To be able to do all of the practical exercises in this tutorial, you will need a complete BTnode developer kit (see Figure 1.2) consisting of: a BTnode rev3; a usbprog USB programming adapter; an ISP programmer (we suggest the Atmel ATAVRISP or alternatively the ATAVRISP MK2 programmer); serial and USB cables; a 15-Pin Molex breakout cable; and the software, documentation and tools contained on the BTnode CDROM (see Figure 1.3). However, a number of exercises can also be performed with a minimal subset of these tools, namely a BTnode, the USB programming adapter, and a USB cable.

For a complete listing of software tools and their respective versions used in this tutorial, please see appendix A. The tutorial assumes that the necessary development tools (avr-gcc toolchain, avr-libc, an ISP programming utility if you use the ISP programmer, Eclipse and CDT) are installed and working correctly. For details on the installation and configuration of the suggested development tools see the BTnode online resources available at `http://www.btnode.ethz.ch`.

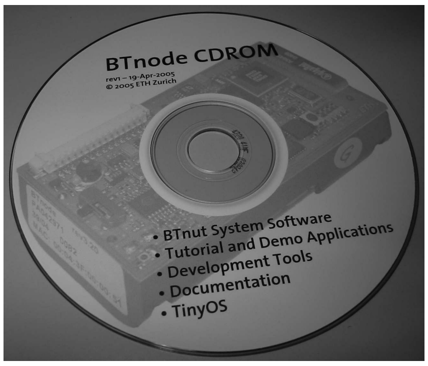


Figure 1.3: The BTnode CDROM.

1.4 Reference Documents

Should you ever need more information than what is given here in this tutorial, feel free to browse the following sites for details on the individual pieces of the puzzle:

- **The BTnode platform reference** – with support documents, installation instructions for the development tools and source software, mailing lists and various links.

  `http://www.btnode.ethz.ch`

- **The home of Nut/OS** – the BTnut operating system core.

  `http://www.ethernut.de`

- **Open source development tools for the AVR platform**

  `http://www.openavr.com`

- **Open source tools for the development on Atmel AVR, Windows platform installer**

  `http://winavr.sourceforge.net`

- **Atmel AVR product family**

  `http://www.atmel.com/products/avr`

- **Atmel AVR related developer information** – application notes, links and tools.

  `http://www.avrfreaks.net`

- **A nice avr-gcc tutorial** (in german)

  `http://www.mikrocontroller.net/wiki/AVR-GCC-Tutorial`

- **Bluetooth Special Interest Group** – all about the standardization, applications and reference documents.

  `http://www.bluetooth.org`

- **Technical BTnode/BTnut support** – For technical questions concerning BTnut and the BTnode platform please inquire to the mailing list:

  `mailto:btnode-development@list.ee.ethz.ch`

1.5 Tutorial Overview

Chapter 2 "First Steps in BTnode Programming" gives a basic introduction of development tools, software structure and documentation sources necessary for development on the BTnode platform. Here we learn how to program an Atmel AVR microcontroller using In-System Programming, compile our first program, use a build system to automate compilation steps and manage software projects using eclipse and CVS.

The chapter 3 "Device Level Programming" introduces simple microcontroller programming and register based input/output as well as interrupts. In chapter 4 "The BTnut Operating System" we introduce higher level concepts of the BTnut operating system. Application structure as well as the terminal library, timers and memory management are discussed. Threads are discussed in a separate chapter "Programming with Threads" (chapter 5).

The chapter 6 "Embedded Debugging" is devoted to different techniques for the debugging and profiling of larger applications where bugs are increasingly hard to find.

After the chapters on the basics about BTnodes and operating systems the remainder of the tutorial is devoted to wireless sensor network application building using basic Bluetooth communication (chapter 7) "Communication Using Bluetooth"), more advanced Blutooth communication with mobile phones in chapter 8 "Interfacing to Handheld Devices" and the usage of the "The Chipcon Radio" in chapter 9.

A short overview regarding "BTnodes and Sensors" is given in chapter 10 where you learn how to use the generic extension interface of the BTnode to attach simple sensor boards and use them in BTnut applications.

Chapter 2

First Steps in BTnode Programming

2.1 Introduction

In this chapter, we will step you through the basic knowledge about development tools, software structure and reference documentation necessary to start developing your own applications on the BTnode platform. This is explained, using a pre-configured toolchain setup on Windows, although other host platforms and tool setups are possible too (Linux and MacOS X). For detailed instructions on the tool installation, please refer to the online documentation and links listed under section 1.4 and the software versions listed in appendix A.

2.2 Development Tools

For basic software development you will need an editor, a compiler-assembler-linker toolchain, a standard library and an in-system programming software to upload the compiled program to your embedded target. There are many other tools that can make life easier when projects are getting larger and debugging more difficult. The selection of tools introduced here should provide you with a basic overview and understanding to define the right set of tools for your personal project needs.

2.2.1 Compilation

The tools introduced here are freely available and are based on GNU GCC and the AVR libc which is a Free Software project whose goal is to provide a high quality C library for use with GCC on Atmel AVR microcontrollers. Together, avr-binutils, avr-gcc, and avr-libc form the heart of the Free Software toolchain for the Atmel AVR microcontrollers. They are further accompanied by projects for in-system programming software (uisp, avrdude), simulation (simulavr) and debugging (avr-gdb, avr-insight, AVaRICE).

These tools are available packaged as a Windows installer in the WinAVR project which we will use as a reference. There are numerous other distributions of the avr-gcc toolchain available as well as different (commercial) compilers for the Atmel AVR family.

A thorough introduction to the internals of such a compiler toolchain as used in embedded systems can be found in Appendix A: Assemblers, Linkers and the SPM Simulator of [7]. Manuals for the avr-binutils, avr-gcc and avr-libc are packaged with the respective distribution or available online (see section 1.4).

The following example illustrates a sample compilation, linkage with startup code and libraries as well as transformation into a machine uploadable format of a sample application called test.c:

```
avr-gcc -c -mmcu=atmega128 -D__BTNODE3__-I../../include test.c -o test.btnode3.o
avr-gcc test.btnode3.o  ../../lib/btnode3/nutinit.o -L../../lib/btnode3 -mmcu=atmega128 -o test.btnode3.elf
avr-size test.btnode3.elf
   text    data     bss     dec     hex filename
  36920    1708     314   38942    981e test.btnode3.elf
avr-objcopy -O ihex test.btnode3.elf test.btnode3.hex
```

2.2.2 Simulation and Debugging

When project size increases and especially in critical situations specialized simulation and debugging tools can be of great benefit. There are numerous tools available (avr-gdb, JTAG tools, Atmel AVR Studio, GNU dwarf parser, avr-insight, Avrora, simulavr) serving different purposes, of which a selection will be introduced in chapter 6.

2.2.3 Project Management

The basic utility used in most build environments is GNU make. The make utility automatically determines which pieces of a large program need to be recompiled, and issues commands to recompile them. This is a very convenient way to avoid retyping long lines of parameters on the command line.

Different editors with syntax higlighting and project management features can be used for C based AVR development. The most common are Eclipse, Emacs, Programmers Notepad and AVR Studio. Especially Eclipse in conjunction with CDT (C/C++ Development Tools) is a very powerful tool that allows C-indexing, project management, integration of a make build environment, debugging, version control and much more.

Version control such as with CVS (Concurrent Version System) or Subversion is helpful for keeping track of changes and sharing source code among team members.

2.2.4 Embedded Target Connection

The software on an embedded system is typically programmed once during manufacturing onto a resident internal memory from where it is then executed. Software changes are frequent during development but infrequent during the lifetime of a product.

For uploading code to the flash memory of the ATmega128l (in-system programming) a serial uploader software (uisp, avrdude, uploader tools in AVR Studio) and an appropriate programmer (hardware) is necessary.

Although basic debugging can be performed via general purpose IOs and LEDs, verbose terminal output is generally preferred. For this a RS-232C serial connection is necessary between the embedded target (BTnode) and a PC. This can be done using a serial level shifter (e.g. Maxim MAX3232) or a USB-serial converter (e.g. Silabs CP2101).

In addition to uploading code using in-system programming as described above, the ATmega128l features a bootloader section as well as JTAG uploading and debugging support (see chapter 6 for further information on JTAG). The bootloader section in the flash memory can be used to re-program the user section of the flash memory once such a bootloader has been installed. See exercise 2.14 for further information.

2.2.5 Documentation Tools

The primary source for information for any hard- or software system are its manuals, typically accompanied by release information, changelogs, readme file and known errata.

The internet is a general resource for developers and project management. More specific mailing lists and archives offer discussion forums on specific topics, such as the avr-libc library usage and development or on BTnode specific issues.

Large online project management such as http://www.sourceforge.net offer many services such as electronic bug tracking systems, version control, web visualization, nightly builds, software distribution and general project management.

Single projects typically extract documentation from source code. This can be done by tools such as javadoc or doxygen to automatically generate up-to-date online documentation.

2.3 Notes on the BTnode Hardware Architecture

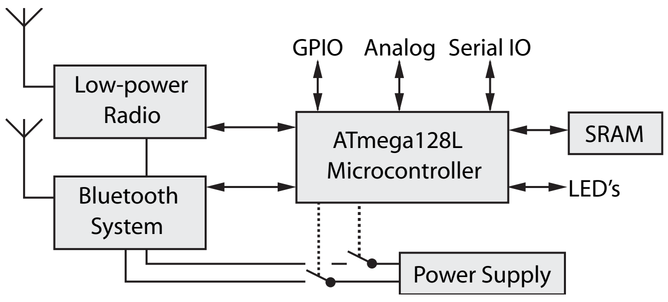


Figure 2.1: BTnode rev3 hardware overview.

System Core – The BTnode System Core consists of an Atmel ATmega128l microcontroller, clocks and SRAM memory.

- Atmel ATmega128l – 4 kB EEPROM, 64 kB SRAM, 128 kB Flash
- System clock – 32 kHz real time clock and 7.3728 MHz system clock
- 5 processor power modes
- External data cache – 3x60 kByte low power SRAM
- Four LED's for easy debugging
- In-system programming through serial ISP programmer, JTAG or resident bootloader

Bluetooth Radio – Zeevo ZV4002 Bluetooth radio running HCI firmware. It is connected to the ATmega128l through a UART interface.

Low-Power Radio – Chipcon CC1000 radio operating at 868 MHz. Other operating frequencies can be used according to the CC1000 documentation (433-915 MHz). Both an integrated monopole antenna, an external wire and an external coaxial connector (MMCX type) are possible though assembly options. The default assembly variant is the internal monopole antenna and operation in the 868 MHz ISM band.

Power Supply – The standard power supply are 2-cell AA batteries. The common range for these is 2-3 V DC when either primary or rechargeable batteries are used. The primary boost converter has a nominal input range of 0.5-3.3 V DC. Alternatively 3.6-5 V can be supplied through the VDC_IN pin available on the external connectors J1 and J2.

- Primary supply – Linear Technologies LTC3429, 600mA max., input 0.5-3.3 V to 3.3 V
- Alternate supply – Linear Technologies LT1962, 300mA max., input 3.6-5.0 V to 3.3 V
- Switchable power-groups for IO, Bluetooth and LPR radio
- Battery charge indicator
- On/Off switch for the primary power supply

A detailed hardware reference is available though the BTnode website (see section 1.4).

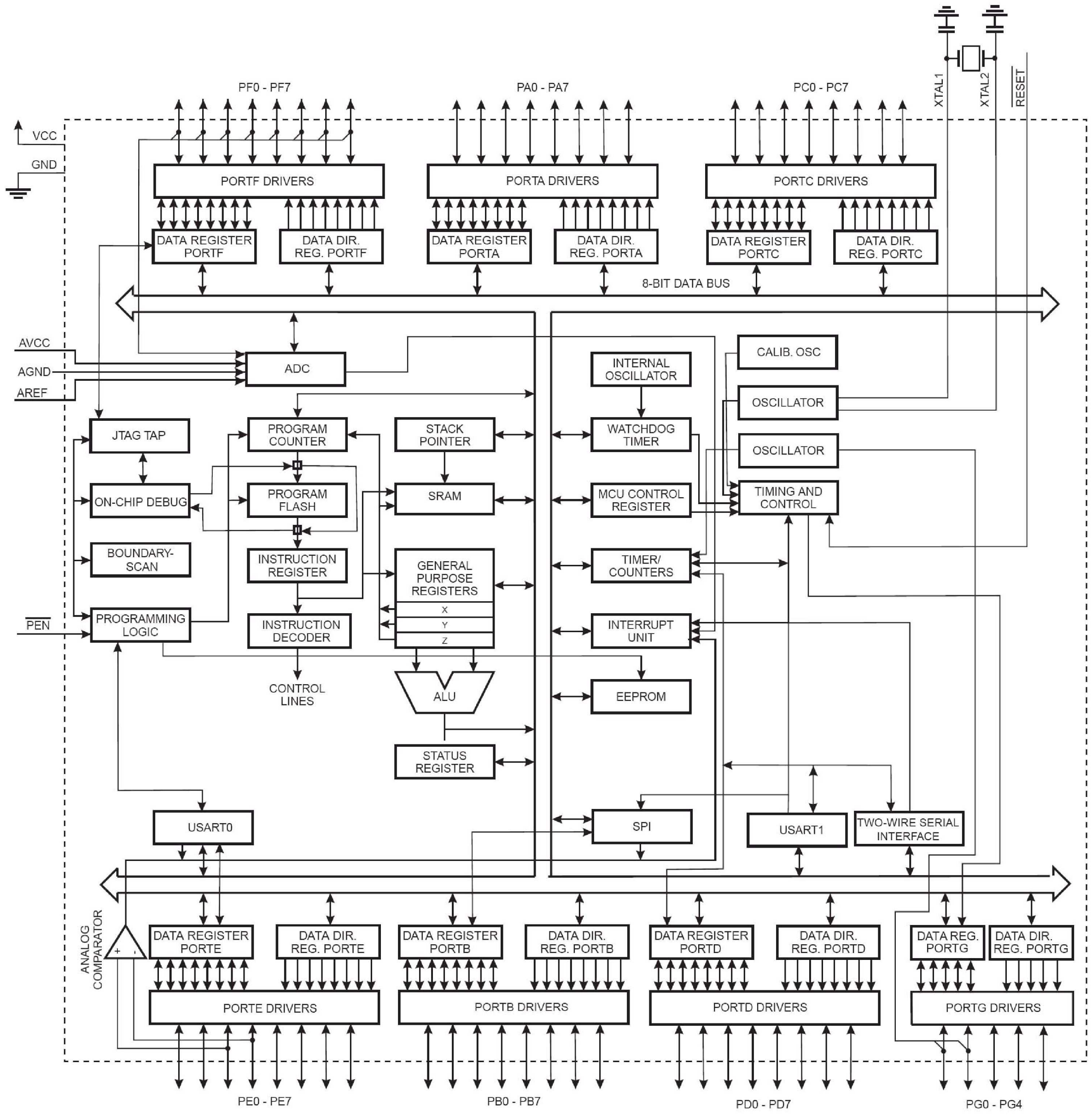


Figure 2.2: Atmel ATmega128l microcontroller core and peripheral block diagram.

Exercise 2.1. *Find the BTnode rev3.20 Schematic and the ATmega128l Processor Manual pdf files [1]. Browse the schematic and find the latch (Texas Instruments SN74LVC573A) used to multiplex the extended SRAMs (AMIC LP62S2048) data and address bus. Which ports of the processor are used to connect to the latch? Which ports are used to connect to the memory?*

Browse for the second latch used to multiplex the LEDs and switchable power supplies. Which port/pin on the ATmega128l maps to which function (LED/power switches) here? Which are the control lines used for the latch? Draw a sample output waveform for the microcontroller pins used, that switch the LEDs on and off.

What are the problems arising from this hardware setup for a software system, especially in the case of an operating system with concurrency (multiple drivers/tasks/threads)? How would you implement a software driver for this functionality? Why is SBI/CBI (set bit and clear bit) not sufficient in this case?

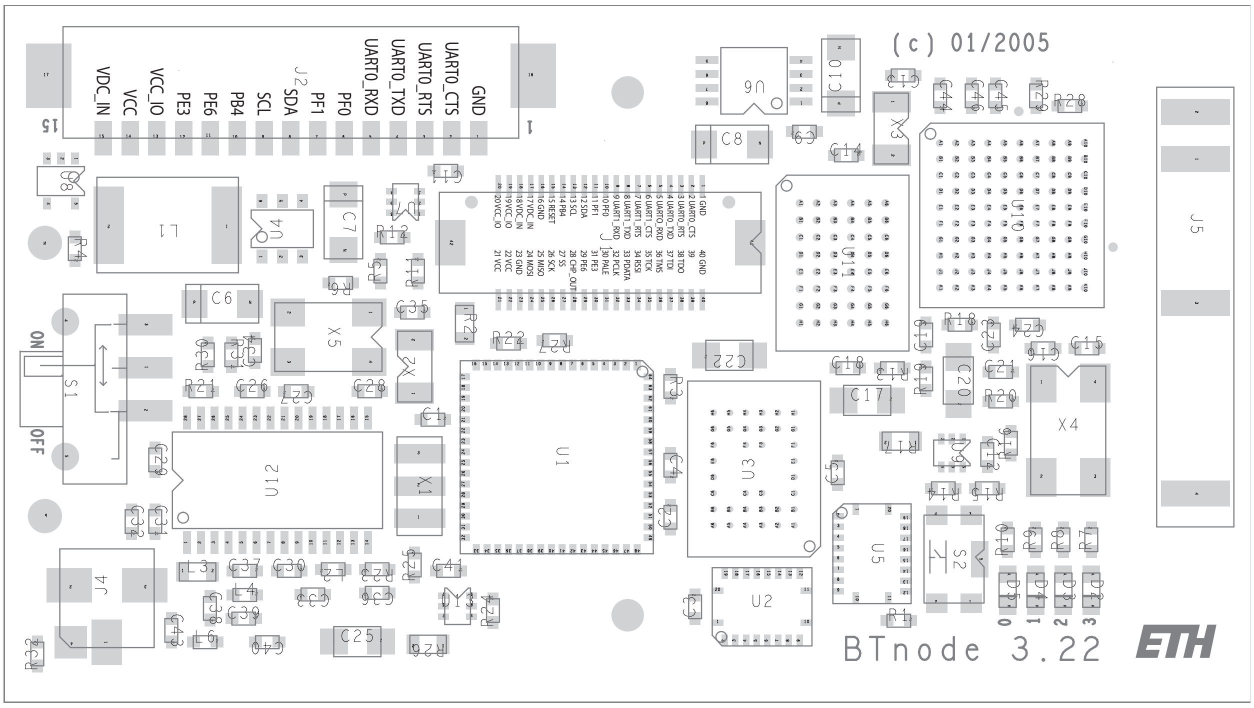


Figure 2.3: BTnode rev3 top assembly and connector pinout.

2.4 BTnut System Software Resources

First, we will make you familiar with the development environment and the tool flow. The exercises in this section are based on using Eclipse and CDT, yet they can also be performed using other project management environments and editors.

Explanation *Getting to know the BTnut system software release*:
The BTnut software is released in both a binary snapshot and sourcecode format. The most recent releases can be downloaded from sourceforge.net.

- The `btnode_snap_btnode3_binary` contains an out-of-the-box pre-compiled library package for AVR binary and documentation, ready for usage with the avr-gcc toolchain and the demo applications included.
- The package `btnut_system` contains all BTnut and Nut/OS sources. It requires to compile the BTnut system software and install the documentation prior to the compilation of applications.

The releases are numbered even and are based on the following CVS tag and date:

```
BTnut snapshot and release -- REL_VERSION = 1.8

Nut/OS -- NUT_SNAPSHOT = 2007-01-23
```

and compiles against the following avr libc:

```
AVR Libc -- avr-libc 1.4.3
```

The BTnut pre-compiled snapshot contains 5 directories, `app` for the applications, `doc` for documentation, `extras` for hardware specific drivers other than the BTnode, `include` for all headerfiles and `lib` for the pre-compiled libraries.

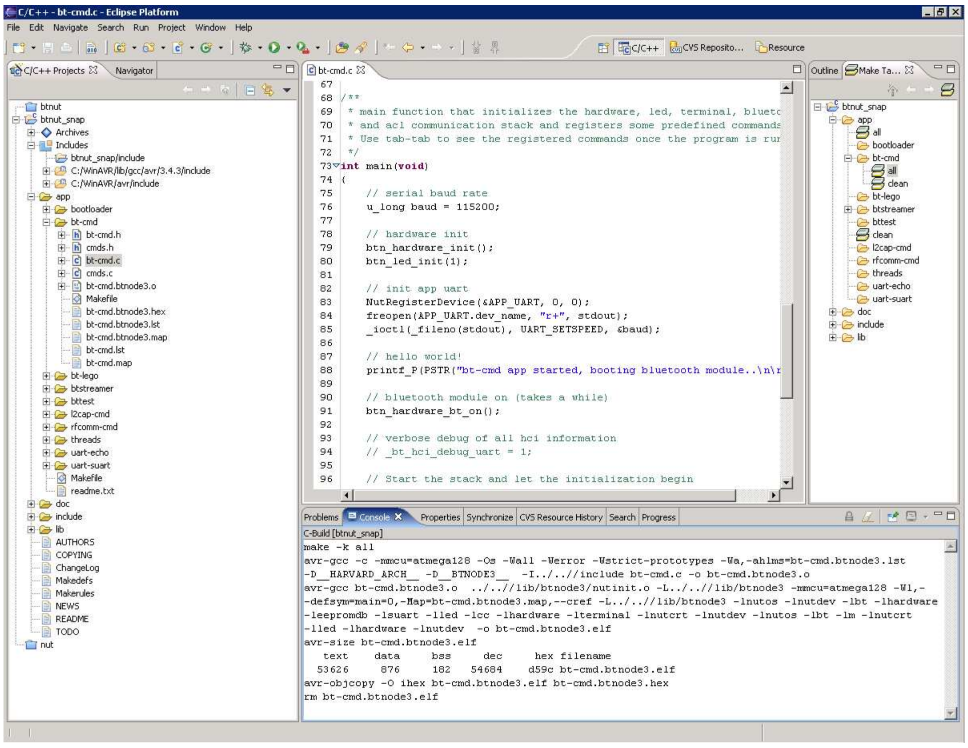
The first task to be performed on the BTnut system software will be to set up a working environment within Eclipse.

Exercise 2.2. *Open the C/C++ perspective in Eclipse. Create a new project called* `btnut_snap_X.X` *by selecting "Standard Make C Project" from the pull-down menu. Be sure to set the correct binary parser on the second screen of the new project wizard (select ELF parser and GNU ELF parser, and enter* `avr-addr2line` *and* `avr-c++filt`*) and set the correct compiler (*`avr-gcc`*) in the discovery options tab to select the correct cross-development tools for the AVR platform.*

Now import the `btnode_snap_btnode3_binary` *package by selecting* `Import`, `Archive File` *into this project. As a final task, you will need to configure the project with the correct include paths for the C/C++ parser: Open the project properties and insert the* `btnut_snap/include`, `$(PATH_TO_AVR_GCC_TOOLS)/avr/include` *and* `$(PATH_TO_AVR_GCC_TOOLS)/lib/gcc/avr/3.4.5/include` *to the projects include paths.*

Exercise 2.3. *Open the* `bt-cmd.c` *file in the* `app/bt-cmd` *folder and go to the line where* `btn_led_init(1);` *is called. Highlight the function name, then press* `F3` *to open the functions* `Declaration` *from the appropriate header file. Right click the function name again and search for* `All References` *in the* `Workspace`*.*

Be sure to switch to the `C/C++ Perspective` *in Eclipse and open the* `C/C++ Projects View` *(see figure 2.4).*



```
/**
 * main function that initializes the hardware, led, terminal, blueto
 * and acl communication stack and registers some predefined commands
 * Use tab-tab to see the registered commands once the program is run
 */
int main(void)
{
    // serial baud rate
    u_long baud = 115200;

    // hardware init
    btn_hardware_init();
    btn_led_init(1);

    // init app uart
    NutRegisterDevice(&APP_UART, 0, 0);
    freopen(APP_UART.dev_name, "r+", stdout);
    _ioctl(_fileno(stdout), UART_SETSPEED, &baud);

    // hello world!
    printf_P(PSTR("bt-cmd app started, booting bluetooth module..\n\r

    // bluetooth module on (takes a while)
    btn_hardware_bt_on();

    // verbose debug of all hci information
    // _bt_hci_debug_uart = 1;

    // Start the stack and let the initialization begin
```

C-Build [btnut_snap]

```
make -k all
avr-gcc -c -mmcu=atmega128 -Os -Wall -Werror -Wstrict-prototypes -Wa,-ahlms=bt-cmd.btnode3.lst
-D__HARVARD_ARCH__ -D__BTNODE3__  -I../..//include bt-cmd.c -o bt-cmd.btnode3.o
avr-gcc bt-cmd.btnode3.o  ../..//lib/btnode3/nutinit.o -L../..//lib/btnode3 -mmcu=atmega128 -Wl,-
-defsym=main=0,-Map=bt-cmd.btnode3.map,--cref -L../..//lib/btnode3 -lnutos -lnutdev -lbt -lhardware
-leepromdb -lsuart -lled -lcc -lhardware -lterminal -lnutcrt -lnutdev -lnutos -lbt -lm -lnutcrt
-lled -lhardware -lnutdev  -o bt-cmd.btnode3.elf
avr-size bt-cmd.btnode3.elf
   text    data     bss     dec     hex filename
  53626     876     182   54684    d59c bt-cmd.btnode3.elf
avr-objcopy -O ihex bt-cmd.btnode3.elf bt-cmd.btnode3.hex
rm bt-cmd.btnode3.elf
```

Figure 2.4: The C/C++ perspective with the C/C++ Projects view on the left, a file editor in the top, console view in the bottom middle and the Make Target view open on the right.

Exercise 2.4. *Open the BTnut System Software Reference (an online version of the BTnut API is available on http://www.btnode.ethz.ch, or locally in* `doc/html`*) in a web browser and open the file*

```
btnode/include/led/btn-led.h
```

from the `File List`*. Read the documentation provided for the* `btn_led_init()` *and* `btn_led_add_pattern()` *functions.*

Exercise 2.5. *Go back to the* `bt-cmd.c` *file and add a new led pattern for the LED heartbeat using* `btn_led_add_pattern` *in line 103. While typing the function name* `btn_led_add_pattern` *press* `CTRL-SPACE` *to invoke Eclipse's* `Content Assist` *function and complete the line with the correct arguments to create a dual blinking LED pattern using these parameters:*

```
pattern = BTN_LED_PATTERN_HALF
arg = 0
speed = 10
nr = BTN_LED_INFINITE
```

Exercise 2.6. *Check the documentation available in the datasheets, application notes, mailing list archives, Nut/OS webpage, Avrfreaks forum, tool resources, etc... to get an overview on the different compilers, libraries, programming variants and hardware programmers available for the Atmel AVR family.*

Exercise 2.7. *Open the avr-libc Manual (online version available on the avr-libc webpage). Find the mathematics functions in the avr-libc and check what functions are supported. Compare this selection to the CPU description found in the ATmega128l Manual and the instruction set of the ATmega128l found in the AVR Instruction Set Manual. Don't forget to read the available footnotes to learn about device specific options.*

Think about what functions you would like to use to implement certain algorithms. Why are function such as `tan()` *present, but simple multiply and divide operations are missing? How would you implement a fixed point division or even floating point operations for the AVR?*

In addition check the `FAQ` *found in the avr-libc Manual* `Related Pages` *documentation (especially entry 2) and the* `General Utilities Module` *of the avr-libc Manual for information on further functions like* `div()`*,* `qsort` *and* `rand()`*.*

Are there other libraries and languages available for the AVR family? Search for possible solutions on the web.

Optional Exercise 2.8. *When linking an application for a microcontroller a startup or initialization code needs to be integrated that controls the bootup and initialization procedure and sets the system into a default state after power-on. This behavior can be specifically controlled by a memory map and init sections. For an introductory documentation of the most common compiler flags and build steps, read through the* `Demo Projects Module` *in the avr-libc Manual.*

This topic is very complex. So we will generally use a pre-configured set up from the BTnut build system to integrate the (hardware dependant) correct startup code and memory map.

Optional Exercise 2.9. *In addition to the* `ChangeLog` *and* `README` *files provided with the BTnut System Software, the project management environment on http://sourceforge.net/projects/btnode has a* `Tracker` *and* `Tasks` *section to track bugs, requests for enhancements (RFEs), support requests etc. Check these locations to learn more about development issues and possible caveats. If you discover a bug either enter it into sourceforge.net or post them on the BTnode mailing list.*

Now you have gained an overview of the BTnut System Software, developing in Eclipse and know how to navigate code and search for documentation.

Explanation *BTnut Configuration Options*:
The BTnut System Software uses a GNU make based build system. The basic configuration is done in a file `Makerules` and parameters are defined in `Makedefs` and can be overridden by setting them as environment variables:

```
BURN = avrdude
BURNPORT = /dev/ttyS0
BURNFLAGS = -pm128 -cavrispv2 -P$(BURNPORT) -s
```

Alternatively you can use uisp with the settings:

```
BURN = uisp
BURNPORT = /dev/ttyS0
BURNFLAGS = -dprog=stk500 -dpart=atmega128 -dserial=$(BURNPORT) \\
--wr_fuse_e=0xFF --wr_fuse_h=0x00 --wr_fuse_l=0xBF

# Defines for btnode3 platform
MCU.BTNODE3   = atmega128
ARCH.BTNODE3  = avr
HWDEF.BTNODE3 = -D__HARVARD_ARCH__ -D__BTNODE3__
DEFS.BTNODE3  = $(HWDEF.BTNODE3)
# further define options
#DEFS.BTNODE3 += -DNUTTRACER
#DEFS.BTNODE3 += -DNUTTRACER_CRITICAL
#DEFS.BTNODE3 += -DNUTDEBUG
#DEFS.BTNODE3 += -DNUT_PERFMON
#DEFS.BTNODE3 += -DBT_L2CAP_SLIMDOWN -DBT_RFCOMM_SLIMDOWN
```

Here, you can select parameters for the default programming interface and define debugging verbosity. We will make use of these features in later chapters of this tutorial.

2.5 First steps in BTnode programming – Using the avr-gcc toolchain

We will now use the tools to compile and upload a first program to the BTnode.

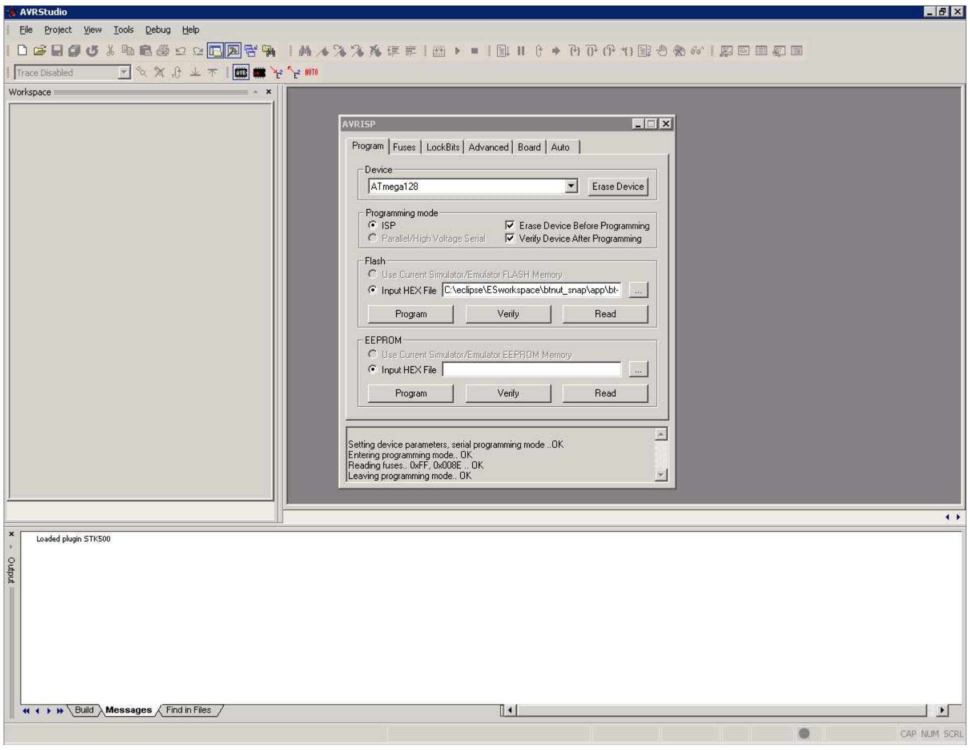
Explanation *ISP Programming Variants*: There are numerous software and hardware components that allow ISP programming of an Atmel AVR microcontroller.

The default tool supported by Atmel is AVR Studio which offers a graphical user interface, simulation and project management capabilities. To use it for programming of an AVR only, open the tool and select the `Program AVR` entry from the `Tools Menu`. Be sure to select the correct device (ATmega128) in the `Program Tab`, do not change the fuse bit settings and select the right `Communications Settings` (Auto) in the Advanced Tab (see figure 2.5). When continuing from the command line be sure to close AVR Studio.

There are numerous command line tools for ISP programming as well. These are often more convenient than the GUI based tools. In the following you will learn to use `avrdude` which also supports a GUI on windows.

For further informations such as using the bootloader function read the Atmel Applications Notes *AVR109: Self Programming*, *AVR910: In-System Programming* and *AVR911: AVR Open-source Programmer.*

Exercise 2.10. *Open a command line shell and check if your avr-gcc toolchain is installed and working correctly. First check the versions of the avr-gcc toolchain by entering* `avr-as --version`, `avr-gcc -v` *and* `avr-ld -v`. *Furthermore we will test* `avrdude -v` *(optional also* `uisp --version`*) that we will later use to upload code to the ATmega128l.*



Device: ATmega128

Programming mode: ISP; Erase Device Before Programming ✓; Verify Device After Programming ✓

Flash: Input HEX File C:\eclipse\ESworkspace\btnut_snap\app\bt-

EEPROM: Input HEX File

```
Setting device parameters, serial programming mode ..OK
Entering programming mode.. OK
Reading fuses.. 0xFF, 0x008E .. OK
Leaving programming mode.. OK
```

```
Loaded plugin STK500
```

Figure 2.5: AVR Studio offers a graphical frontend to programming, simulation and project management functions.

Optional Exercise 2.11. *To see specific hints and help on the toolchain, execute the tools with the* `--help` *parameter from the command line or the man pages (unix) to get detailed online help.*

Exercise 2.12. *Now connect a BTnode to your PC using a usbprog board and a USB cable (see figure 2.6). Further connect an Atmel ATAVRISP programmer to the usbprog board and to a serial port on your PC. The default settings are* `/dev/ttyS0` *for programming through an ATAVRISP and* `/dev/ttyUSB0` *for debugging through the serial port of the BTnode. (If in doubt about the right serial port for debugging use the* `List_USB2UART` *script on windows or check* `/var/log/messages` *on linux.).*

Try to communicate with the ATAVRISP and the ATmega128l on the BTnode:

```
avrdude -pm128 -cavrispv2 -P/dev/ttyS0
```

Explanation *Using the USB-UART adapter board*: The usbprog rev2 board is used for a breakout of all pins available on connector J1. Furthermore it contains a USB to UART converter (Silabs CP2101) that is used to connect the debug UART of the ATmega128l to a PC (default usage). A dedicated connector for ISP programming is also available on the usbprog board. Also when using the USB connection, the BTnode is remotely powered from the PC to save battery power.

Be sure to orient the usbprog board correctly as shown in figure 2.6. The board goes above the power switch of the BTnode with the two mounting holes matching those on the BTnode. If in doubt about the right serial port for debugging use the `List_USB2UART` script on windows or check `/var/log/messages` on linux.

Exercise 2.13. *Now upload a first pre-compiled application to your BTnode. Download the newest example application file* `bt-cmd.btnode3.hex` *from the BTnode project sourceforge.net file release page. Open a command line shell. In this step you will two use* `avrdude` *commands that are executed by the ISP programmer:* `erase` *and* `upload`*. First erase any programs present in the flash memory of the ATmega128l using* `erase`*:*

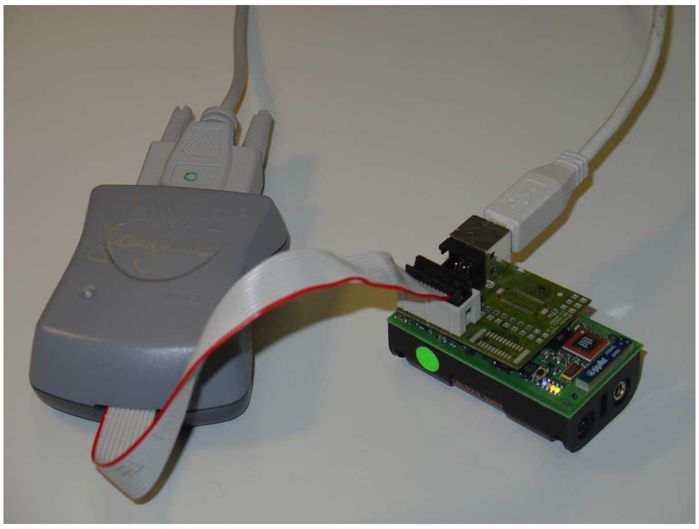


Figure 2.6: Debugging a BTnode using a USB connection to a serial port and ISP programming with the Atmel ATAVRISP.

```
avrdude -pm128 -cavrispv2 -P/dev/ttyS0 -e
```

Then program the new application code from an Intel Hex file format to the BTnode using `upload`*:*

```
avrdude -pm128 -cavrispv2 -P/dev/ttyS0 -D -V -s -U flash:w:bt-cmd.btnode3.hex:i
```

The `-D` *flag disables the auto-erase function, the* `-V` *flag disables auto-verify and the* `-s` *flag requires safemode. You can add the* `-v` *flag to receive more verbose output. Observe the LEDs on the BTnode for output from your first uploaded program.*

Explanation *Installing the bootloader*: Download the newest bootloader file `bootloader.btnode3.hex` from the BTnode project sourceforge.net file release page. To install the bootloader, proceed to upload this program code to the BTnode using the ISP programmer as described analogously for `bt-cmd.btnode3.hex` in exercise 2.13. Now your BTnode is ready to receive software flash reprogramming instructions.
To compile your own bootloader, navigate to the `btnut_system/btnut/app/bootloader` folder. Compile the bootloader by executing `make btnode3`. You should now have a file called `bootloader.btnode3.hex`.

Optional Exercise 2.14. *An alternative to using the ISP programmer is using a bootloader on the BTnode that can emulate ISP behaviour. The bootloader may or may not be installed on your BTnode but can be built from source code and installed using the method introduced in the previous exercise. See the explanation box below for more information.*

Now, to upload the program code:

1. *press **and hold** the reset button on the BTnode*
2. *execute the upload command below*

   ```
   avrdude -pm128 -cavrisp -P/dev/ttyS0 -D -s -U flash:w:bt-cmd.btnode3.hex:i
   ```

3. *release the reset button on the BTnode*

If you can't find the reset button, see figure 2.7. If you get strange error messages while programming, try to disconnect and reconnect the USB cable.

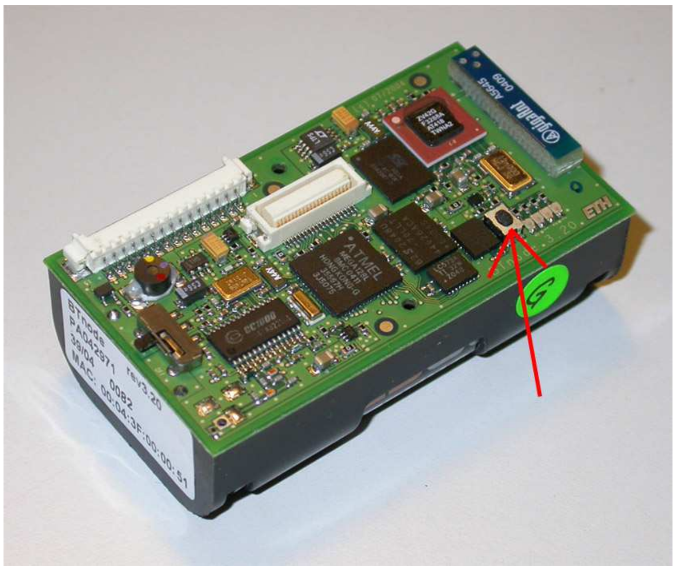


Figure 2.7: BTnode reset button

Exercise 2.15. *Erase the* `bt-cmd` *application on the BTnode. Open a terminal programm to the serial port you have connected your usbprog board with* `57.6k`, `8N1`, `no handshake` *to observe the terminal output from the BTnode.*

Upload the simple application `uart-echo.btnode3.hex` *with uart output to the BTnode. As soon as the uart-echo application responds, you can type and see the response on the LEDs. This time use the auto-erase function and auto-verify on avrdude:*

```
avrdude -pm128 -cavrispv2 -P/dev/ttyS0 -s -U flash:w:uart-echo.btnode3.hex:i
```

WARNING: DO NOT USE OTHER LOW-LEVEL COMMANDS WHEN IN-SYSTEM PROGRAMMING UNLESS YOU KNOW WHAT YOU ARE DOING AS IT COULD DAMAGE THE MICROCONTROLLER!.

Exercise 2.16. *Now go back to the* `bt-cmd` *application in Eclipse that we modified earlier and save the changes we have made. Open a command line shell on this directory. Compile the* `bt-cmd` *application by entering:*

```
make btnode3
```

Then upload the newly compiled application to the BTnode with:

```
make btnode3 upload
```

Observe the different LED heartbeat compared to the pre-compiled `bt-cmd.btnode3.hex` *we uploaded earlier. Check the terminal program for output. Hit* `Tab` *twice to get a selection of commands possible in the* `bt-cmd` *application. Explore the different functions available in this demo application. Try to locate different BTnodes by issuing* `bt inquiry sync`.

Explanation *The bt-cmd demo application*: The `bt-cmd` demo application is a brief example of how to use the Bluetooth radio and protocol stack. Once the application has booted and is ready on a serial terminal with `57.6k`, `8N1`, `no handshake` you can check the list of available commands by hitting `Tab` twice.

```
# ----------------------------------------------------
# Welcome to BTnut (c) 2006 ETH Zurich
# bt-cmd program version: 20060405-1206
# $Id: firststeps.tex,v 1.15 2007/01/22 16:40:02 beutel Exp $
# running @ 7.3628 MHz, NutFreq=10241 Hz
# ---------------------------------------------------
booting Bluetooth module...
Bluetooth MAC address: 00:04:3f:00:00:d2
HCI version: 2 00C9 2 0012 003D
LMP features: 03 10 00 FF FF 05 F8 1B
Local name: 'ZeevoEmbeddedDevice'
hit tab twice for a list of commands
[bt-cmd@00:d2]$
bt      led     bat     nut     log
[bt-cmd@00:d2]$
```

There are NutOS/BTnode and Bluetooth specific commands (if called without arguments they will show hints on the correct syntax, where applicable).
`bt` – bluetooth radio commands
`led` – toggle LED patterns
`bat` – get the battery status
`nut` – show OS system information
`log` – BTnut logging features

For reference on Bluetooth [6] see the support documents and links provided on the BTnode web-page (see section 1.4).

Exercise 2.17. *To simplify the building and uploading we will now create* `Make Targets` *in Eclipse that you can execute with a single click.*

Open the `Make Targets View` *(Window → Show View → Other → Make) and navigate to the* `app/bt-cmd` *folder. Right click onto this folder and select* `Add Make Target`*. Alternatively you can create different targets by entering make arguments such as* `all`*,* `btnode3`*,* `version` *or* `clean`*.*

Then use these `Make Targets` *to automatically build and upload selected applications from within Eclipse. You can observe the progress and console output from the respective views.*

Exercise 2.18. *Right click onto the* `bt-cmd.c` *file in the* `C/C++ Projects View` *and select* `Compare With Local History` *to see the changes you have made earlier.*

Exercise 2.19. *Create a new folder in the* `app` *directory and copy the* `bt-cmd/Makefile` *to this folder. Create (or alternatively copy and rename) a new* `application.c` *file in this folder. Be sure to edit the project name in the* `Makefile`*.*

Now you are ready to program your first own project using BTnut.

Explanation *Resetting the work environment to initial conditions*: The pre-compiled BTnut snapshot used in this tutorial can be obtained from http://sourceforge.net/projects/btnode, section Files. Download the `btnut_snap_btnode3_binary_x.x.tar.gz` file and unpack it to a location of your choice. Now create a new `Standard C/C++ Project` in Eclipse and import the files from the `btnut_snap_avrbinary` archive.

Optional Exercise 2.20. *In order to stay up to date on the bleeding edge development codebase of BTnut you will need to check out the most current version from the CVS repository on sourceforge.net. Open the* `CVS Repository Exploring` *perspective in Eclipse and create a new CVS repository:*

```
Host: btnode.cvs.sourceforge.net
Repository path: /cvsroot/btnode
```

```
User: anonymous
Connection type: pserver
```

The check out the CVS `HEAD` *of the module* `btnut` *as a* `Standard Make C Project`*. You can check for changes to the most current CVS tag* `HEAD` *or to other dates and tags by selecting* `Compare With...` *or* `Replace With...`*.*

Before building the demo applications in the `app` *directory you will need to check out a release of Nut/OS either by executing* `make nut_cvs_sources` *in the btnut directory or by checking it out from CVS into a parallel project as described above (host* `btnode.cvs.sourceforge.net`*, repositorqy* `/cvsroot/ethernut`*, module* `nut`*. The build the BTnut libraries first by executing* `make clean` *and* `make all` *in the* `btnut` *directory.*

Chapter 3

Device-Level Programming

3.1 Introduction

The goal of this session is to familiarize the reader with some peculiarities of programming microcontrollers that have a rich set of peripherals. After going through the tutorials and exercises, you should be able to understand and write simple drivers which allow you to use these peripherals efficiently. To work through the whole chapter takes you approximately four hours, without the optional exercises about two hours.

In this session, we will avoid using library functions and operating system support as far as possible. The reason is that you should be able to really understand what is going on instead of using some black-box functionality. Clearly, this type of programming is often a bit cumbersome. But you will enjoy the comfort and convenience of an operating system that you will learn to use in the next session all the more.

In Section 3.2, the use of off-chip resources is explained using the example of the LEDs on the BTnodes. In Section 3.3, the reader learns how to use the analog-digital converter of the ATmega128 as an example for an on-chip resource. In Section 3.4, we introduce interrupts. The final Section 3.5 deals with critical sections that are required to protect shared data.

3.2 Off-chip resource: Setting and Clearing LEDs

As a first example, we now use the LEDs on the BTnode. The reason for this choice is that for any further work with the BTnodes, we need some kind of feedback from the programs we implement. The LEDs are an *off-chip* resource. Unfortunately, accessing the LEDs is a bit tricky and requires some "hacks", which are explained in the following.

The address bus of the ATmega128 is 16 bit wide and it is mapped to the ports A (lower 8 bits) and C (upper 8 bits). The address bus is mainly needed to access the external SRAM (AMIC_LP62S2048), but at the same time it is also connected to the LEDs via a latch. To set or clear LEDs, the bits that determine whether the LEDs should be on or off have to be put on the address bus. Then the latch is enabled, i.e. it samples the value on the address bus. After a while, the latch is disabled, i.e. it holds the previously samples value. The following function does exactly this:

```
void write_led(u_char value) {
    volatile u_char * pointer;
    u_char dummy;

    // compute the pseudo-address that contains the values for the LEDs
    pointer  = (u_char *) ( ((u_short)value) << 8);
    // force the compiler to write this pseudo-address to the address-bus
    dummy    = *pointer;
    // now enable the latch
    PORTB |= 1<<PB5;
    // wait a moment
    asm volatile  ("nop" ::);
    // disable the latch, i.e. hold the value
    PORTB &= ~(1<<PB5);
}
```

Explanation *volatile*: Note the keyword `volatile` before the declaration of `pointer`. It tells the compiler that code lines containing `pointer` should not be optimized at all. This is necessary because the compiler does not know anything about external off-chip resources like the LEDs. Thus it cannot understand why we compute the variable `dummy`, which is never used afterwards. If `volatile` were omitted, the compiler would simply ignore such “nonsense” statements.

Explanation *Accessing special purpose registers*:
The names of special purpose registers are defined in the `hardware/btn-hardware.h` header file and in header files included therein. These names can be used like variables. For example you may read the content of the `PORTB` register using

```
u_char current_portb = PORTB;
```

Similarly, you can write to such a register in the same way as you write to a variable, e.g.

```
PORTB = 0xff;
```

sets all bits of the `PORTB` register to one.
Most often however, you only want to read or write a single bit of a special purpose register. This can be done by using the bitwise *and* / *or* operators. The names of individual bits are also defined in the header files. But these names cannot be used like variables, they are simple aliases for the position of the corresponding bit within a register. For example `PB5` is an alias for 5 since the `PB5` bit is the fifth bit within the `PORTB` register (counted from the left starting with 0). Examples:

```
if (PORTB & (1<<PB5)) // checks whether the PB5 bit is set
PORTB |= 1<<PB5;      // sets the PB5 bit to one
PORTB &= ~(1<<PB5);   // clears the PB5 bit
```

Exercise 3.1. *To check whether you have understood how LEDs are controlled, use the BTnode schematics to figure out the* `value` *needed to switch on the blue LED. Explain the computation of* `pointer`*.*

As a start, we write a program that blinks with the blue LED. The main routine thus looks as follows:

```
#include <hardware/btn-hardware.h>

int main(void) {
    DDRB |= 1<<DDB5;
    while (1) {
        // toggle the blue LED
        // wait a second
    }
    return 0;
}
```

Explanation *Configuring the direction of IO ports*:
The line before the infinite loop configures the fifth bit of the `DDRB` register. DDRB stands for Data Direction Register of Port B and this operation declares the fifth pin of port B to operate as an output pin. After this line, you are free to use the `write_led` function shown above. See pages 63ff in the ATmega128 manual for a detailed explanation.

Exercise 3.2. *Complete now the program sketched above. In order to see what your program does, you will have to implement a `pause` function. Do this using a loop that increments a counter variable.*

Optional Exercise 3.3. *Once your program is running, try to estimate the clock frequency of the ATmega128. Do this by counting the operations in the loop of your pause function.* **HINT:** *Look at the list file (`<program name>.lst`) which has been created by the compiler. Even without understanding any assembler at all you can find your function by searching for its name. You can identify the loop by looking at the labels ("`.L6:`", for example) and the branch instructions ("`brlo .L6`", for example). Assume that all assembler instructions take one cycle to execute.*

3.3 On-chip resource: The Analog to Digital Converter

The ATmega128 microcontroller contains an on chip analog to digital converter (ADC), whose detailed description can be found on pages 231 to 247 of the ATmega128 manual. As for all on-chip resources, the ADC can be configured by writing to special purpose registers, its status and the conversion result can be accessed by reading from special purpose registers. In the case of the ADC, the two 8 bit registers called ADMUX and ADCSRA are used for configuration and status. The two 8 bit registers called ADCH and ADCL are used to deliver the conversion result.

As we now know how to use the LEDs, we can start writing more complex programs. We now want to sample the battery power and show the result using the LEDs. The solution should look as follows:

```
#include <hardware/btn-hardware.h>

int main(void) {
    int battery_power;
    DDRB |= 1<<DDB5;
    while (1) {
        battery_power = get_battery_voltage();
        // if battery_power below 1000mV, switch on red LED
        // if battery_power between 1000mV and 2000mV, switch on yellow LED
        // if battery_power above 2000mV, switch on green LED
        // wait a second
        // switch on blue LED
        // wait a second
    }
    return 0;
}
```

We now have a more detailed look at the function `get_battery_voltage`. Its skeleton looks as follows:

```
int get_battery_voltage(void) {

    // configure ADMUX
    ADMUX |= 1<<MUX0;
    ADMUX |= 1<<MUX1;

    // configure ADCSRA register such that the conversion
    // is as slow as possible and the ADC is enabled

    // start conversion and wait for result

    // read (and convert ?) result
}
```

In a first step, the `ADMUX` register is configured. As you can see in the manual, page 244, all bits are cleared at startup and we only have to write the bits which we want to be one. Looking at BTnode schematics, we see that the `BAT_SENSE` signal is connected to pin 3 of port F. From the manual, page 239 we know that this pin is the third channel of the ADC and table 98 on page 244 tells us that we have to set the bits `MUX1` and `MUX0` from the `ADMUX` register to sample the voltage from channel three. We leave the `ADLAR` bit cleared. The `REFS1` and `REFS0` bits are left cleared because we use the external voltage reference connected to the `AREF` pin of the ATmega128.

WARNING: DO NOT USE OTHER SETTINGS FOR THE REFSx BITS, IT COULD DESTROY THE MICROCONTROLLER!.

Exercise 3.4. *Now its your turn to configure the `ADCSRA` register. For maximal precision, we want the slowest conversion speed. We do not use interrupts and we want to do a single conversion.*

After having configured the ADC, the conversion can be started. This is done setting the `ADSC` bit of the `ADCSRA` register. This bit is automatically cleared when the conversion is completed. Wait for this condition and then read the result from the `ADCL` and the `ADCH` register.

Determine the values you expect from the ADC for a battery voltage of 1 volt and 2 volts, knowing that the reference voltage is 3300 millivolts, the ADC delivers 10 bit values and the `BAT_SENSE` signal is half the battery voltage (see schematics).

HINT: *If your conversion result is always zero, make sure that (i) you either have batteries in your BTnode or you have connected the battery contacts to an external power supply and that (ii) the power switch is on (if connected to the USB cable, the BTnode is also powered if this switch is off, but then the* `BAT_SENSE` *signal is 0).*

3.4 Writing interrupt routines: Hardware Timers

In this section, the program from the previous section is modified such that it periodically samples the battery voltage in a timer interrupt routine. The advantage is that now the microcontroller can do other work in parallel. The processor load created by the timer interrupt is measured using an IO pin and the oscilloscope.

Explanation *Hardware Timers*:
Another type of on-chip resources are timers. In principle, timers are counters that are incremented automatically. By the use of configuration registers, the speed of incrementing the timers can be adjusted and whenever the timers overflow or reach a specified value, they trigger an interrupt.

Explanation *Interrupt Service Routines (ISR)*:
Interrupts are used to execute a function, the so-called interrupt service routine. The normal program flow (the main function, in our case) is interrupted and the interrupt service routine is executed. As soon as it terminates, the normal program flow is resumed exactly at the position where it was interrupted.

Timer interrupts can thus be used to execute some periodic functionality without having to spend the whole processing time on waiting. An example is shown here:

```
#include <hardware/btn-hardware.h>
#include <dev/irqreg.h>

static void timer3IRQ(void *arg) {
    // switch on green led
}

int main(void) {

    // register interrupt service routine
    NutRegisterIrqHandler(&sig_OVERFLOW3, timer3IRQ, 0);
    // configure the speed of the timer
    TCCR3B |= 1<< CS30;
    TCCR3B |= 1<< CS32;
    // enable the interrupt at overflows of the timer
    ETIMSK |= 1<< TOIE3;

    while (1) {
        // toggle the blue led
        // wait a second
    }
    return 0;
}
```

In addition to the main routine, the interrupt service routine (ISR) `timer3IRQ` is defined. At the very begin of main, `timer3IRQ` is registered as the service routine for the `sig_OVERFLOW3` interrupt, that is for the event that timer 3 overflows.

After registering the ISR, the timer is configured. The `CS30` and `CS32` bits of the `TCCR3B` register are set to configure the speed of the timer. In this case, the timer is incremented every 1024 clock cycles (see page 135 of the manual). The timer does not have to be started, it is always active. However, the generation of interrupts when the timer overflows has to be enabled. This is done by setting the `TOIE3` bit of the `ETIMSK` register.

Exercise 3.5. *We now will modify the previous program, such that the battery power is sampled in a timer ISR. Use timer 3 in such a way that the battery power is sampled approximately once every two seconds. The ISR displays the sampled result on the LEDs, but in contrast to the previous program, it does not wait and switch on the blue LED.* **HINT:** *To adjust the interval of the ISR, you can change the prescaler (*`CS3x` *bits) and/or set the timer manually to a non-zero value after every overflow.*

Optional Exercise 3.6. *Modify the program from the previous exercise using the* clear timer on compare match (CTC) *mode of the hardware timer, which is described on page 121 and 131ff. Also use the ISR to display the result of the battery power sampling using the LEDs as in the previous example.*

In a real-world program, often a large number of different interrupts are used to service multiple peripherals at the same time. By default, interrupts are blocked while an ISR is executing, thus different interrupts can block each other. Therefore the careful programmer aims at keeping ISRs as short as possible.

Optional Exercise 3.7. *Measuring the execution time of an ISR can be done as follows: On a free IO pin of the ATmega128, we generate a rising edge at the begin of the ISR and a falling edge at the end. The time that the IO pin is high can then be measured on an oscilloscope. For example we may use pin 0 of port F, which is a good choice since it is accessible as pin 6 on the 15-pin-connector of the BTnode, as you can verify on the BTnode schematics. Connect this pin and ground (e.g. from pin 1 of the 15-pin-connector) to the oscilloscope. Set up pin 0 of port F as an output pin using the* `DDRF` *register. How long takes your ISR to execute? How much of the processing power is thus used for sampling the battery power every two seconds?* **HINT:** *If you only have an analogue oscilloscope, you may have to decrease the interval of the ISR drastically (e.g. 10ms is a good value) in order to display the generated waveform properly.*

3.5 Protecting shared data and resources

In this section, the program from the previous section is extended to write measured data to the terminal. It is explained why this should not be done from interrupt context. Thus the sampled data has to be shared by the ISR, which determines the battery voltage and the main routine, which prints it to the terminal. It is explained why this shared data has to be protected from uncoordinated concurrent access by multiple flows of control and how this can be done.

Explanation *Using the terminal*:
The ATmega128 has also two serial interfaces, so called Universal Asynchronous Receiver Transmitter (UART) units. The UART1 is used to connect the ATmega128 to the Bluetooth module. The UART0 can be used to write ASCII text to the terminal, which is a program running on the host computer. Writing text to the terminal can be done using the well-known `printf` function from the avr-libc. Most standard conversion strings (e.g. `%d` for signed integers) and special characters (e.g. `\n`) can be used, but not all. For example the float conversion (`%f`) is not implemented.

```
int variable = 13;

printf("Hello world, ");
printf("my lucky number is %d\n",variable);
```

The `printf` function writes a formatted string to the standard output stream. But before using `printf`, we have to setup the standard output stream explicitly, that is we have to define that we want to link the standard output to the UART0. This can be done using a routine like to following:

```
#include <hardware/btn-hardware.h>
#include <stdio.h>                // freopen
#include <io.h>                   // _ioctl
#include <dev/usartavr.h>         // NutRegisterDevice, APP_UART, UART_SETSPEED

void init_stdout(void) {
    u_long baud = 57600;

    btn_hardware_init();
    NutRegisterDevice(&APP_UART, 0, 0);
    freopen(APP_UART.dev_name, "r+", stdout);
    _ioctl(_fileno(stdout), UART_SETSPEED, &baud);
}
```

To read data from the terminal, you can use the function `fscanf`.

Optional Exercise 3.8. *Write a program, that samples the battery voltage once every two seconds using a timer ISR. Instead of displaying the result on the LEDs, print it to the terminal from within the ISR. Measure the execution time of the ISR using the oscilloscope.*

The measurement of the execution time of the ISR shows that `printf` takes a lot of time. We have discussed before that ISRs should be as short as possible. Therefore we want to do the printing of the sampled battery voltage from the main routine. Of course we want to print every measurement result exactly once.

Exercise 3.9. *Rewrite the program from Ex. 3.8 such that the battery voltage is sampled in the ISR but that the printing of the result is done in the main routine. To do this, you have to think about some communication mechanism between the two flows of control.*

Optional Exercise 3.10. *Instead of printing the result from reading the* `ADCL` *and* `ADCH` *registers directly, print it in millivolts.* **HINT:** *Remember that an unsigned short variable overflows at 65536, thus be careful about the data types you use.*

The program you have written probably works just fine. But if you would have a lot of time to observe its behavior (or if you are “lucky”), you would notice that sometimes strange values are printed on the terminal.

Explanation *Corruption of Unprotected Data*:
If two flows of control, e.g. the main routine and an ISR access a piece of data, its value can become corrupted. Assume that the ISR writes to a 16 bit variable which is read by the main routine. Assume that its value at some point of time is `0x00ff`. Now the main routine first reads the upper byte, that is `0x00`, and then the ISR is executed. The ISR may increment the variable to `0x0100`. After the ISR has terminated, the main routine continuous reading the variable and reads the lower byte as `0x00`. Now the main routine has read the variable as `0x0000`, which is far off the real value of either `0x00ff` or `0x0100`.

This problem can be solved by using *critical sections*, that is by protecting the access of a shared variable in the main routine from being interrupted by an ISR. The other way round is no problem, since an ISR cannot be interrupted by the main routine.

Explanation *Enabling and Disabling Interrupts*:
To protect a piece of code from being interrupted, you can disable interrupts globally using the function `cli()`. To reenable interrupts, you can use the function `sei()`. These instructions clear and set the I-bit of the `SREG` register, which is the main status register of the ATmega128 microcontroller.

Exercise 3.11. *Protect the shared data that is used in your program from Ex. 3.8. Do this by implementing the functions `EnterCritical` and `ExitCritical`. Make sure that `ExitCritical` does not enable interrupts if they were disabled before `EnterCritical`.*

Optional Exercise 3.12. *Not all data access conflicts are so easily visible as the shared variable from Ex. 3.8. For example our implementation of the `write_led` function has a problem of this kind too. Explain why and fix it.*

Chapter 4

The BTnut Operating System

4.1 Introduction

In this chapter, we introduce the BTnut operating system (OS). In comparison to the exercises of the previous chapter, this has two main consequences:

- You do not have to read hardware schematics and spec sheets when you want to use resources, since we are now able to use library functions. In this chapter you will use such functions for accessing the LEDs and the terminal. Also the analog to digital converter that we have used in the last chapter would be accessible through such library functions – see the `dev/adc.h` header for a description. There is even a function `btn_bat_measure` that does exactly what we have done manually (see `hardware/btn-bat.h`).
- Complicated programs can be divided into a set of threads. Programming a single thread is often much easier than programming the whole functionality in a single program. At the same time, however, programming with multiple threads becomes more complicated. Even though the execution coordination of these threads is done by the operating system, we still need to properly code concurrent threads, especially when it comes to two or more threads using a common resource (e.g., the radio, or the terminal). Threads will be described in the following chapter, where we introduce the API of the BTnut OS for creating, executing and terminating threads, as well as for the communication and coordination of such threads.

The following sections will explain the anatomy of a simple BTnut program using the example of LED control (section 4.2). Section 4.3 will then explain how we can use BTnut to provide output over a terminal connection (i.e., through the USB cable).

4.2 Anatomy of a BTnut Program

Recall from chapter 1 that BTnodes run an embedded systems OS from the open source domain, called Nut/OS. Nut/OS is designed (among others) for the Atmel ATmega128 microcontroller (which is used on the BTnodes), and is thus an excellent base on which the BTnut extensions provide additional device drivers to access BTnode-specific hardware. The actual compilation of your programs (i.e., the translation of C-code into machine-code) is done using `gcc-avr` (part of `WinAVR` on Windows), which is a freeware C compiler (and assembler) for the Atmel processor platform. We thus have three parts to our BTnode OS-experience: the rudimentary C-libaries as implemented by `gcc-avr`'s *avr-libc*; the higher-level OS routines built on top of *avr-libc* by Nut/OS; and the BTnode-specific device drivers provided by BTnut. In the following, we will simply call this layered OS architecture "BTnut", yet one should keep the differences in mind in order to better understand the overall system operation.

We first look at a minimal BTnut program.

Explanation *A minimal BTnut program*: BTnut programs are written in C (though we don't have access to all libraries that we are used from our PCs). Just as any other C-Program, the feature a `main` function as the initial focus of control, i.e., this is the first function that gets executed after power-up of your BTnode. However, in contrast to regular PC programs, our BTnut programs must *always* begin with initializing the BTnode hardware:

```
#include <hardware/btn-hardware.h> // for btn_hardware_init

int main(void)
{
    /* ALWAYS call this func at the beginning of main */
    btn_hardware_init();          /* initialize SRAM */

    for(;;)
    {
        // do something clever here
    }

    /* main should never return (where to?!) */
}
```

Another peculiarity of a BTnut program is that it should never actually finish. In contrast to a PC program, one cannot return to the command line after the execution of a particular application is done – BTnodes are expected to continously execute their task! If their main program ends, the behavior of a BTnode is undefined (it might simply restart, or stop altogether, or . . .).
HINT: Do not put a `return 0;` or similar statement at the end of `main`, even though `main` is defined as having an `int` return value. This allows the compiler to throw an error during compilation in case the last line of your program should ever be reached (it shouldn't, really!).

Obviously, an empty program is not very exciting. Let's see how the LED control described in the previous chapter can be implemented through BTnut OS function calls.

Explanation *Using the on-board LEDs*: BTnut OS offers through `<led/btn-led.h>` the functions `void btn_led_set (u_char nr)` and `void btn_led_clear (u_char nr)`, where `nr` denotes the LED in question, namely 0 through 3. Before the LEDs can be controlled this way, we need to initialize them first:

```
#include <hardware/btn-hardware.h> // for btn_hardware_init
#include <led/btn-led.h>           // for led-related functions

int main(void)
{
    btn_hardware_init();          /* initialize SRAM */
    btn_led_init (0);             /* initialize LEDs */

    btn_led_clear (0);    btn_led_set (1);
    btn_led_clear (2);    btn_led_set (3);

    for(;;);                      /* endless loop */
    /* main should never return (where to?!) */
}
```

Notice the argument that `btn_led_init` takes – it indicates whether we want to activate an *LED heartbeat*, i.e., the periodic blinking of one or more LEDs to indicate that our BTnode is "alive" (as we didn't want a heartbeat in the above example, we used 0). For more information on LED heartbeats, see page 36.

Exercise 4.1. *Write a program that endlessly rotates through the four LEDs (i.e., it turns one after another on and off). Observe the output. Use* `for` *statements to slow the rotation down until it becomes easily visible.*

Optional Exercise 4.2. *Have your program from Ex. 4.1 terminate after a few rotations (you will need to add* `return 0` *to the end to get it to compile). What behavior do you observe?*

4.3 The Terminal

In order to communicate back to the user (or programmer), we are not restricted to using the on-board LEDs only. Through our USB-cable, we can setup our BTnode in such a way that `printf` statements provide output that can be printed in a terminal program on our PC, and use `fscanf` to read user input from within the terminal program and input it back into our BTnut program. This is where the ATmega128 UART ports – Universal Asynchronous Receiver Transmitter – come into play. Actually, the ATmega128 supports USART ports – Universal Synchronous/Asynchronous Receiver/Transmitter. Consequently, you will notice that some libaries and functions actually use `usart` in their names. However, as it does not make much of a difference, and as UART is the much more common interface, we will continue to use that term.

The ATmega128 has two UART interfaces – UART0 and UART1. While UART0 is used to connect the ATmega128 to the Bluetooth module, we can use UART1 to write ASCII text to the *terminal*, i.e., a program running on the host computer that uses well-known communication protocols to send and receive text from a remote computer. See the online documentation at `http://www.btnode.ethz.ch` for information on how to setup a terminal program under Linux (e.g., `minicom`) or Windows (e.g., Hyperterm).

Explanation *Setting up the terminal*: The `printf` function writes a formatted string to the standard output stream. But before using `printf`, we have to setup the standard output stream explicitly, i.e., we have to define that we want to link the standard output to the UART1. This can be done using a routine like to following:

```
#include <stdio.h>                  // freopen, includes <io.h> for _ioctl
#include <dev/usartavr.h>           // NutRegisterDevice, APP_UART, UART_SETSPEED

void init_stdout(void) {
    u_long baud = 57600;

    NutRegisterDevice(&APP_UART, 0, 0);
    freopen(APP_UART.dev_name, "r+", stdout);    // "r+": read+write
    _ioctl(_fileno(stdout), UART_SETSPEED, &baud);
}
```

Once we have established a terminal connection, we can write text to it using the well-known `printf` function (which is provided for the ATmega128 platform in *avr-libc*). Most standard conversion strings (e.g. `%d` for signed integers) and special characters (e.g. `\n`) can be used, but not all. For example, the float conversion (`%f`) is not implemented as the ATmega128 does not support floating point operations. **HINT:** Exit the terminal program again before trying to upload a new program to the BTnode, otherwise the bootloader's upload replies will be caught by the terminal program, not your upload tool (i.e., the upload will fail).

```
int main(void)
{
    btn_hardware_init();           /* initialize SRAM */
    init_stdout();
    int variable = 13;
    printf("Hello world, ");
    printf("my lucky number is %d\n",variable);
    for (;;);                      /* main should never return */
}
```

To read data from the terminal, you can use the function `fscanf`. However, in order to read input from the user, we can use an already defined library – `<terminal/btn-terminal.h>` – which offers convenient access to user input. Specifically, through the use of `btn-terminal`, a programmer can define a set of *commands* and optional arguments that a user can execute from a terminal prompt. Upon hitting the Tab-key, the BTnode terminal program lists all available commands.

Explanation *The Interactive Terminal*: The BTnode terminal is defined in `terminal/btn-terminal.h`. After initializing it with the stream to use and prompt to display, the programmer simply has to "run" it:

```
#include <hardware/btn-hardware.h>
#include <dev/usartavr.h>          // NutRegisterDevice, APP_UART, UART_SETSPEED
#include <terminal/btn-terminal.h>  // for interactive terminal, includes stdio.h and thus io.h

int main(void) {
    btn_hardware_init();
    init_stdout();                          /* as defined above */
    btn_terminal_init(stdout, "[btn3]> ");
    printf("\nHowdy!\n");
    btn_terminal_run(BTN_TERMINAL_NOFORK, 0); /* NOFORK never returns */
}
```

After the usual initializations (for an explanation of `init_stdout`, see page 29), the terminal thread is initialized with `btn_terminal_init`, the first argument links it with the UART of the standard output stream, the second argument defines the prompt of the command line (you may use any string you like). Finally, the command `btn_terminal_run(BTN_TERMINAL_NOFORK, 0)` starts the terminal. The function never returns, unless you use `BTN_TERMINAL_FORK` as the first parameter, in which case the terminal is started in a separate *thread*. We will explain threads in chapter 5.

Using a terminal program such as *minicom* or *Hyperterm*, we can now interact with our BTnode program. However, except for a small message and a prompt, there isn't yet much we can do. Fortunately, BTnut already comes with a few commands that we can readily make available in our terminal.

Explanation *Predefined Terminal Commands*: The BTnut OS offers sets of predefined terminal commands. To use them, they have to be registered. Two of these sets, with the corresponding header file and the register function, are given below. Similar command sets also exist for the bluetooth radio (`bt_*`) and the debug logger (`log_*`).

```
#include <terminal/btn-cmds.h>
    btn_cmds_register_cmds();

#include <terminal/nut-cmds.h>
    nut_cmds_register_cmds();
```

The register commands have to be called after `btn_terminal_init` and before `btn_terminal_run`. For example, `btn_cmds_register_cmds` provides the *led* command, `nut_cmds_register_cmds` provides the *nut* command, which has several sub-commands. Hit the Tab-key for a list of available commands.

Exercise 4.3. *Incorporate the default BTnut commands into your small terminal application. Use the* nut threads *command to show the currently running threads. Now include* `led/btn-led.h` *and add a call to* `btn_led_init(1)` *right after initialization. Also, add* `NutSleep(1000)` *to the final* `for`*-loop so that it isn't empty (this needs* `sys/timer.h`*). Observe the output of* nut threads *now.*

Exercise 4.4. *Change the call to* `btn_terminal_run` *to use* `BTN_TERMINAL_FORK` *as its first parameter (you can leave the second argument "0" right now) and check the output of* nut threads *again.*

Explanation ***Creating your own Terminal Commands*:** You can also register your own commands with `btn_terminal`. You must provide a function with a standardized interface (a pointer to a single argument of type `char`), which can then be registered under an arbitrary command name:

```
void _cmd_square(char* arg) {
    int val;
    if (sscanf(arg,"%d",&val)==1) {
        printf("The square of %d is %d\n",val,val*val);
    }
    else { printf("USAGE: square <value>\n"); }
}

int main(void) {
    ...
    btn_terminal_init(stdout, "[btn3]> ");
    btn_terminal_register_cmd("square",_cmd_square);
    btn_terminal_run(BTN_TERMINAL_NOFORK, 0);
    for (;;);
}
```

The command *square* is registered with `btn_terminal_register_cmd` *after* the initialization of the terminal. The first parameter is the string you will have to type to launch the function, whose identifier is given as the second argument. Note that functions that you want to register as a commands must have the signature `void <functionname>(char* arg)`.

Exercise 4.5. *Write a program that registers the command* echo*, which simply echos all the given arguments.*

Optional Exercise 4.6. *Write a program that registers the commands* myset *and* myclear*, which will take the numbers 0-3 as an argument, and set or clear the given LED.*

4.4 Timers

Explanation ***Timers in BTnut*:** Instead of using `for`-loops or `NutSleep` calls, you can also use one or more *timers* to schedule recurring function calls. Using timers, you can easily parallelize your program without the need for explicit thread-management: simply create a function for each required aspect of your program, and register different timers for each of them. BTnut will then take care of calling these functions in the given intervals.

```
#include <hardware/btn-hardware.h>
#include <sys/timer.h>

HANDLE hTimer;

static void _tm_callback(HANDLE h, void* a) { . . . }

int main (void)
{
    btn_hardware_init();
    hTimer = NutTimerStart( 3000, _tm_callback, NULL, 0 );
    for (;;) { NutSleep (1000); } /* never end */
}
```

You can use `NutTimerStart` and `NutTimerStop` to install or remove periodic timers. Using `TM_ONESHOT` as the last parameter to `NutTimerStart` will automatically remove that timer after it has run once (i.e., after one interval) – using "0" instead installs a periodic timer.

Exercise 4.7. *Write a program with two timed callback functions: one should repeatedly turn on the blue LED (using `btn_led_set(LED0)`) and switch off the red LED (using `btn_led_clear(LED1)`), the other shall do the opposite, i.e. turn on the red LED and switch off the blue LED.*

Optional Exercise 4.8. *Write a program that periodically calls a function to "shift" the current LED by one position (after the last position, it should begin again with the first).*

Optional Exercise 4.9. *Create a terminal application that allows to control the LED shifting functionality implemented in Ex. 4.8, i.e., use* `btn_terminal_register_cmd` *to create a command "toggle" that turns the shifting on or off.*

4.5 Dynamic Memory Management

Typically there is no need for dynamic memory management in your BTnode program. Simply create global or local variables, and the BTnut OS (together with `gcc-avr`) will take care for you to properly allocate the ATmega128 SRAM (of which we have 64kBytes) for the stack and the global and/or static variables.

However, should the need arise (e.g., you might want to limit the stack size of your current thread, or you have temporary data that is very large), BTnut also supports dynamic memory allocation using `malloc` and `free`.

Explanation *Dynamic Memory Allocation*: If you need to allocate memory directly, you can use Nut/OS's own `malloc` and `free`:

```
#include <hardware/btn-hardware.h>
#include <stdlib.h> // malloc, free
#include <string.h> // memset

u_int BUF_SIZE = 4096;

int main(void) {
    char *buffer;
    btn_hardware_init();

    buffer = malloc(BUF_SIZE);
    if (buffer) {
        /* fill buffer with data */
        memset(buffer, 0xFF, BUF_SIZE);
        /* and free it again (really useful) */
        free(buffer);
    } else { /* out of memory */ }

    for (;;);  /* endless loop */
}
```

In addition to the 64kBytes of directly accessible SRAM, the BTnode also features three banks of *external data cache* – each having 60 kBytes – for a total of 180 kBytes of external storage. This memory cannot be allocated directly from within our BTnut program, as our ATmega128 processor can only address 64 kBytes of RAM. Instead, one has to briefly switch the upper 60 kBytes of our "regular" SRAM with one of the three available banks, in order to access data in there. This functionality is implemented in the `cdist/xbankdata.h` and can be tested by including the `terminal/xbank-cmds.h` commands.

See the sources of `terminal/xbank-cmds.c` in the `btnut`-sourcetree if you want to learn more about banked memory. In this tutorial, we will not further elaborate on this feature of the BTnut OS.

Chapter 5

Programming with Threads

5.1 Introduction

In this chapter, we introduce thread programming with BTnut. A *thread* is simply a function or a small program that can run concurrently to another thread. Using threads, we can actually write BTnode programs that listen to incoming commands over their radio, periodically measure sensor values, compute intermediate results, and send data to other nodes. All (virtually) at the same time!

This *multithreading* is handled by Nut/OS, as obviously our ATmega128 microcontroller can only handle one instruction at a time. In order to support multithreading (or multitasking) on a single core processors, the operating system needs to repeatedly start and stop individual threads (i.e., *schedule*) – in a completely transparent fashion. Two general approaches to multithreading exist:

- *Preemptive:* The OS has complete control over processes and can stop, pause, and restart them (almost) at will. Most modern PC operating systems (e.g., Linux, Windows 2000/XP) use preemptive multitasking. This is because it allows for a more reliable distribution of resources.

- *Cooperative:* Processes need to manually give up control of the CPU to a central scheduler, which then evaluates which thread or task should come next based on process priorities and queues. While cooperative multithreading simplifies resource sharing, and usually results in faster and smaller code (making it thus more suited to embedded systems programming), it runs the risk that a poorly designed or "hung" process can bring the entire system to a halt.

Nut/OS – and therefore also BTnut – employ *cooperative multithreading.* This means that in order to execute two or more threads at the same time, each process needs to periodically give up control to the OS scheduler. This will be described in more detail in section 5.3 below, right after we explain how to create our own threads in section 5.2. Sections 5.4 and 5.5 finally introduce the concepts of *mutexes* and *events*, respectively, which are means of coordination and communication between threads.

5.2 Creating Threads

Using BTnut, we can easily define and run our own threads. First we look at how threads are defined.

Explanation *Creating Threads*: Threads are functions. As mentioned earlier, the main routine itself is also a thread, which is started automatically after startup (fortunately, this is completely transparent to the programmer, thanks to Nut/OS). Additional threads have to be declared using the `THREAD` macro. An example defining the thread `my_thread` is shown below.

```
#include <sys/thread.h>

THREAD(my_thread, arg) {
    for (;;) {
        // do something
    }
}
```

Functions that are used as threads are supposed to never return, thus to loop endlessly (if you want to end a thread, you will need to manually call `NutThreadExit`). The second argument of the `THREAD` macro, called `arg` here, is a void pointer and can be used to pass an argument of arbitrary type to the thread when it is created (note that the actual *declaration* of `arg` as a void pointer is done by the macro). Don't forget to include `<sys/thread.h>` for working with threads!

The thread `my_thread` is now defined, but it has to be started before it becomes active.

Explanation *Running Threads*: A thread can be activated by any other thread, e.g. by the main routine. This is done using the command `NutThreadCreate`.

```
#include <sys/thread.h>

int main(void) {
    if (NutThreadCreate("My Thread", my_thread, 0, 192) == 0) {
        // Creating the thread failed
    }
    for (;;) {
        // do something
    }
}
```

The first parameter defines a name for the thread, the second parameter is the name of the function we have defined before. The third argument is a pointer that is passed to the thread function (compare with the second argument `arg` of the `THREAD` macro) – we do not use this feature here and thus an arbitrary value can be used. The last argument is the size of the stack that is allocated for the thread. This stack is used for local variables and for passing arguments when calling subroutines. If this value is chosen too large, the system may run out of heap memory. If it is chosen too small, the thread overwrites memory that is used otherwise, which results in unpredictable behavior. See page 30 for a method to check whether your stack size is correctly chosen. For now, just use 192 and you will be fine.

Exercise 5.1. *Write a program that creates a thread as explained above. This thread shall repeatedly turn on the blue LED (using `btn_led_set(LED0)`) and switch off the red LED (using `btn_led_clear(LED1)`) (***HINT:*** `LED0` and* LED1 *are just macros for the numbers we were using before, i.e., "0" and "1", respectively. However, using symbolic names instead of numbers makes our programs more portable). The main routine, after having created the thread, shall do the opposite, i.e. turn on the red LED and switch off the blue LED. Which LEDs are switched on? Why? Add a single `NutThreadYield` such that the other LED is switched on. Add a second `NutThreadYield`, such that both LEDs are switched on by turns (you will see both LEDs switched on, because the main routine and the thread alternate very quickly).*

5.3 Thread Control

Exercise 5.1 has demonstrated the cooperative nature of the BTnut OS. In order to have two or more threads running, they need to repeatedly and continously *give up control* of the CPU and other resources, so that other threads may run.

In principle (we will see an exception later on), active (i.e., running) threads only yield the CPU to other threads if this is explicitly coded. The most simple way to do this is `NutThreadYield`, a function that has no parameters. This function causes the OS to check whether other threads with higher priority are ready to run (we will explain thread priorities below). If this is the case, the current thread is suspended, i.e. `NutThreadYield` does not return and the thread with the highest priority among those that are ready to run is given the CPU. If no ready-to-run thread has a higher priority than the current thread, `NutThreadYield` returns immediately.

Explanation *Giving up Control*: In order to support concurrent threads on the BTnode, each thread, even the `main()` function, must periodically yield control. A call to `NutThreadYield` basically means "Is there any process that is more important than myself? If so, feel free to take over control. Otherwise, I will simply continue." Once control has been given away and is returned at a later point in time, the thread will continue to run right after the call of `NutThreadYield`.
If a thread has nothing to do, it can also force cease of control by calling `NutSleep(time)`. This function puts the current thread into SLEEPING mode and transfers control to any thread that is waiting for control (i.e., is READY, see below). If no thread is waiting, the *idle* thread takes over, which is always ready-to-run (but which has the lowest priority – see below).
Note that threads might also give up control involuntarily – in case of an *interrupt*. See the BTnut documentation for details.

Explanation *BTnut System Threads*: We have already encountered a number of threads before, created and run by the BTnut OS: the LED thread (see page 28 and excercise 4.3), the terminal thread (see section 4.3 and excerise 4.4), as well as the idle thread and the main thread (again from exercises 4.3 and 4.4). We can visualize the currently active threads using the `nut threads` command (see *Predefined Terminal Commands* on page 30):

```
[bt-cmd@00:d2]$ nut threads

Hndl Name     Prio Sta QUE  Timr StkP FreeMem
2057 T_TERMIN  150 RUN 0385 0000 200D   950 OK 2057 0D6A
14A4 LED       150 SLP 0000 2088 1481   989 OK
1087 main       64 SLP 0000 2074 1064   733 OK
0D6A idle      254 RDY 0385 0000 0D4E   356 OK 2057 0D6A
```

In order to have all of these "standard" threats running at the same time, we also need to make sure that *all* of them repeatedly yield the CPU to other threats. As the idle, LED, and terminal threat are all coded for us by the OS programmers (who thoughtfully made all of these threats yield every so often), we only need to make sure that the *main* threat (which is under our control) does so as well!

Exercise 5.2. *Use the minimal BTnut program as described on page 28 and add a LED heartbeat (see page 28) and the predefined Nut/OS terminal commands (see page 30). Start the terminal in a new thread using* `btn_terminal_run(BTN_TERMINAL_FORK, 0)`*, but leave the main routine empty (i.e., use only* `for(;;)`*). Do you see the LED heartbeat? Can you interact with the terminal? Fix your program so that both heartbeat- and terminal-thread can be executed concurrently to your (empty) main program.* **HINT:** *See Ex. 4.3 and 4.4.*

Explanation *Controlling the LED Thread*: Initializing our LEDs with `btn_led_init(1)` also starts a separate *LED thread*. The LED thread displays dynamic patterns on the LEDs, typically to indicate that the program is still running ("heartbeat"). Its pattern can be set with a single command, i.e., using `btn_led_add_pattern` or `btn_led_heartbeat`. See the BTnut system software reference for a detailed description of these commands. By default, the LED thread starts to blink with the blue LED after initialization.
Note that even when the heartbeat is active, we still can switch on and off LEDs individually using the commands `btn_led_set` and `btn_led_clear`. The LED thread will remember the pattern it was showing before LEDs are switched on manually and restart displaying the pattern after all these LEDs are cleared again manually.

Exercise 5.3. *Write a program with a main routine and an additional thread. Both threads repeatedly write a message to the terminal and then yield (using* `NutThreadYield`*). What do you observe? (***HINT:** *you can freeze terminal output in minicom using Ctrl-A) Do you have an explanation?* **HINT:** *Writing to the terminal is done with the speed of the UART, e.g., 57600 bits per second, which is slow in comparison to the speed of the CPU.* **HINT No. 2:** `printf` *does not directly write to the UART, instead it writes to a buffer with a limited capacity (default is 64 characters).*

Explanation *Thread Priorities and States*: Each thread in BTnut has a *priority* – a value from 0–254. The *idle* thread has the lowest possible priority, 254, while *main*, as well as all manually created threads, have a default priority of 64.
Priorities become important if several threads are competing for control. Each thread can be in three different states: RUNNING, READY, or SLEEPING. While only one thread can be RUNNING at any moment in time (this is managed by the BTnut OS), several can either be READY or SLEEPING. A sleeping process has ceded control either by calling `NutSleep(time)` (and is woken up by the OS after at least *time* milliseconds have passed) or is waiting for an *event* (e.g., an incoming radio signal, or a message from another thread – more about this in section 5.5 below).
Once the running thread cedes control using `NutThreadYield`, its state becomes READY, and BTnut transfers control to another ready-to-run thread – the one with the highest priority. If all other ready-to-run threads have a *lower* or at most equal priority, control is returned to the yielding thread immediately (otherwise some unknown time later). Multiple threads with the same priority are executed in FIFO order.

Explanation *Setting Thread Priorities*: Remember that in the BTnut OS, threads have a priority in the range of $[0, 254]$, where a lower value means a higher priority. The default priority is 64. You may assign the current thread a higher priority, e.g. 20, using

```
THREAD(my_thread, arg) {
    NutThreadSetPriority(20);
    for (;;) {
        // do something
    }
}
```

Note that changing the priority of a thread implies a `NutThreadYield` (i.e., setting its state to READY), thus potentially yielding the CPU to another thread. This is the case if the running thread reduces its priority, and is thus no longer the thread with the highest priority that is ready to run.

Exercise 5.4. *Take the program from Ex. 5.1 and give the self-created threat a higher priority. Compare the output with the original program from Ex. 5.1. Repeat the experiment giving the self-created thread a lower priority. What do you observe?*

Optional Exercise 5.5. *Repeat Ex. 5.3 but give the additional thread a higher priority. Compare the output with what you received in Ex. 5.3. Repeat the experiment giving the additional thread a lower priority. What do you observe?*

Optional Exercise 5.6. *Repeat Ex. 5.3 but use* `NutSleep` *instead of* `NutThreadYield`*. Why is the output different from Ex. 5.3?*

Explanation *Terminating Threads*: A thread can terminate itself as shown below.

```
THREAD(my_thread, arg) {
    for (;;) {
        // do something
        if (some condition)
            NutThreadExit()
    }
}
```

There is no easy way for some thread A to kill another thread B. Nevertheless, you will implement this functionality in Ex. 5.13.

Combining thread creation with our means of writing command-line applications for the terminal (see section 4.3), we can experiment with thread creation and termination more conveniently:

Exercise 5.7. *Write a program that registers the command* create *as a terminal command. This command takes a string argument and creates a thread with this name. This thread periodically prints its name on the terminal and then sleeps for a second.* **HINT:** *A thread can access its own name using* `runningThread->td_name`*, e.g., using* `printf("%s ready\n",runningThread->td_name)`.

Optional Exercise 5.8. *Rewrite the program from Ex. 5.7 such that the first thread you start sleeps for one second, the second thread sleeps for two seconds, etc.* **HINT:** *For this purpose, you may use the third argument of the* `NutThreadCreate` *to pass the sleep time to the thread. Another alternative would be to use a global data structure.*

Optional Exercise 5.9. *Rewrite the program from Ex. 5.7 so that the* create *command takes a second parameter specifying the stack size of the thread that is created. Use this command and* nut threads *to figure out how much stack is actually used by the threads you create. Add some local variables to these threads and/or call some dummy functions from these threads to see how this increases the amount of used stack.*

5.4 Sharing Resources: Mutual Exclusion (Mutex)

Ex. 5.3 showed the problem of two or more threads trying to access the same resource (the terminal) concurrently. As a result, their output was garbled. One way to coordinate shared resources is the use of a *mutex* – a lock mechanism for *mutual exclusive* resource usage.

Explanation *Mutexes in BTnut OS*: Shared resources can be used exclusively by a thread by signaling current use over a mutex. After defining a mutex using `NutMutexInit(&myMutex)`, threads can use `NutMutexLock` and `NutMutexUnlock` to reserve the resource managed by the mutex:

```
#include <hardware/btn-hardware.h>
#include <dev/usartavr.h>         // NutRegisterDevice, APP_UART, UART_SETSPEED
#include <stdio.h>
#include <io.h>
#include <sys/thread.h>

#include <sys/mutex.h>

MUTEX myTerminal;

THREAD(my_thread, arg) {
    for (;;) {
        NutMutexLock(&myTerminal);
        printf ("This is Thread One\n");
        NutMutexUnlock(&myTerminal);
        NutThreadYield();
    }
}

void init_stdout(void) {  . . . }

int main(void) {
    btn_hardware_init();
    NutMutexInit (&myTerminal);
    init_stdout();                          /* as defined previously */

    if (0 == NutThreadCreate("ThreadOne", my_thread, 0, 192)) {
            printf ("Sorry, could not create ThreadOne. Stopping...\n");
            for (;;);
    }
    for (;;) {
            NutMutexLock(&myTerminal);
            printf ("This is the Main Thread\n");
            NutMutexUnlock(&myTerminal);
            NutThreadYield();
    }
}
```

Exercise 5.10. *Rewrite the program from Ex. 5.3 so that each thread first acquires a mutex lock before printing to the terminal.*

Exercise 5.11. *Write your own little "thread-safe"* `printf` *function that uses mutexes in order to exclusively acquire use of the terminal.* **HINT:** *You can either use a separate function call (e.g.,* `my_printf`*) or a preprocessor macro (e.g.,* `PRINTF`*). Using a macro should simplify argument handling, as* `gcc` *supports so-called* variadic macros*:*

```
#define PRINTF(...) {  \
  /* acquire mutex */  \
  printf (__VA_ARGS__) \
  /* release mutex */  \
}
```

5.5 Events

Another important part of a multithreaded OS is *communication between threads*. This allows the coordinated use of multiple processes, as threads can signal other threads when to wake up, or in general inform a number of threads that they have finished processing a particular data structure.

Explanation *Sending and Receiving Events*: The coordination (synchronization) of threads can be done using BTnut *events*. Consider the example shown below:

```
#include <sys/event.h>

HANDLE my_event;

THREAD(thread_A, arg) {
    for (;;) {
        // some code
        NutEventWait(&my_event, NUT_WAIT_INFINITE);
        // some code
    }
}

THREAD(thread_B, arg) {
    for (;;) {
        // some code
        NutEventPost(&my_event);
        // some code
    }
}
```

Here we see two threads. Thread `thread_A` executes some code and then blocks in the `NutEventWait` function. It only continues when either an event is posted or the timeout expires. The timeout is specified in milliseconds with the second parameter. In the example shown above, the timeout is disabled, i.e. an infinite time is specified with the macro `NUT_WAIT_INFINITE`.

Exercise 5.12. *Write a program with three threads (main and two additional threads) and a global variable with initial value 2. The three threads shall execute in turns, which you implement with events. One thread computes the square of the global variable, the second decrements it by one and the third multiplies it by two. All threads print the result on the terminal. When the global value has reached a value greater than 10000, all threads except the main routine terminate themselves. The main routine enters an endless loop.*

Exercise 5.13. *Extend the program from Ex. 5.7 with the terminal command* kill *that takes the name of a previously created thread as an argument. The terminal thread shall use an event to inform the selected thread that it is supposed to kill itself.*

Optional Exercise 5.14. *What happens if first an event is posted by some thread A and only afterwards some thread B does a* `NutEventWait` *? What happens if multiple events are posted before another thread is ready to receive them? Are the events stored or lost? Write a program to find out.*

Optional Exercise 5.15. *What happens if two threads are waiting for the same event? Are both threads woken up? Do thread priorities play a role? Write a program to find out.*

Exercise 5.16. *Modify the program from Ex. 5.13 so that each created thread mostly sleeps (e.g., using* `NutSleep(15000)`*) and only* briefly *listens for a kill signal (e.g., using* `NutEventWait(&killqueue, 125)`*). Observe what happens if you send a process a kill signal. Does it eventually terminate? Try changing the signal wait command to* `NutEventWaitNext(&killqueue, 125)`*. Can you still terminate a thread with your* kill *command? Why? Search the BTnut API for answers.*

Explanation *Events Signaling in Nut/OS*: When a signal is posted to an event queue (e.g., using `NutEventPost`), Nut/OS checks to see if any thread is waiting for a signal on this queue (using `NutEventWait`). If there are threads waiting, Nut/OS takes the *first* thread only (i.e., the one with the highest priority) and sets its status from SLEEPING to READY. Since posting events with `NutEventPost` implies a `NutThreadYield`, the posting thread will also become READY. Depending on the priority of the available ready-to-run-threads, Nut/OS might continue with the posting thread, switch to the signaled thread (i.e., the one that was waiting), or even execute a completely different ready-to-run-thread with an even higher priority than those two.
If you want to "wake up" all threads waiting on a particular queue, not just the one with the highest priority, you can use `NutEventBroadcast` instead.

Explanation *Asynchronous Events*: When a thread posts a signal to a particular event queue using `NutEventPost` or `NutEventBroadcast`, Nut/OS might switch control to another thread as these two function calls also imply a `NutThreadYield` (and thus a switch from the RUNNING state to the READY state). In order to continue running, a thread may use so-called *asynchronous* variants of those two functions – `NutEventPostAsync` and `NutEventBroadcastAsync`, respectively – in order to continue being in the RUNNING state. Both routines perform exactly the same signaling as their regular counterparts, yet without executing a context switch. This can be done later using, e.g., a `NutThreadYield` or `NutSleep`.

Exercise 5.17. *In order to gain understanding of threads and thread coordination, we will now write a ping pong game. We have two players standing at opposing ends of a table that hit a ball back and forth, and every time a player misses the table, the other player scores. The player that first reaches 11 points wins.*

In order to implement this, we will need two players (0 and 1), one ball, and one coordinator (referee) that keeps track of points. The sequence of events will look as follows:

1. *The current player will play the ball (initially player 0).*
2. *The ball will move across the table, and either hit or miss the table.*
3. *In case the ball misses the table, the referee scores one point for the opponent. If this player has reached 11 points, the referee ends the game and declares this player winner.*
4. *The sequence repeats at point 1, with player 0 and 1 alternating turns. If the last ball missed the table, the next player will serve, otherwise the point just continues until one player misses the table.*

Implement this algorithm on the BTnode. All the actors in the game will be implemented as a separate thread, coordination among threads is achieved through events. The coordinator records the score and outputs messages to the terminal. After the game finishes, the program ends, but make sure the `main` method never returns, otherwise the BTnode reboots and starts a new game!

HINT: *The ball will be responsible for deciding whether or not it hits the table, i.e. whether the player hits the ball well or not. In order to 'decide' whether a ball hits the table, we will use a random number generator. At the beginning of the program, you will need to include `stdlib.h` and initialise the random number generator by calling* `srand(u_int seed)`. *From then on, every call to `rand()` will give a number between `0` and `RAND_MAX`, so in order to get a random number r number between a and b (a <= r < b), use `a + rand() % (b-a)`. Experiment with different 'player qualities', i.e. using a higher probability of playing a good ball and see how it influences the result. Make ample use of* `NutSleep` *in order to make the game "watchable" on the terminal window.*

Chapter 6

Embedded Debugging

6.1 Introduction

The goal of this tutorial is to get to know the different tools and techniques for embedded debugging considering the BTnode platform as example.

One of the most compelling problems for anyone programming an embedded system, is to understand what your system is doing, what resources it's using and how it interacts with the external world. Bugs occur. Fixing them is usually easier than finding them! The problem is that embedded code cannot be easily executed under a debugger, nor can it be easily traced, because of the following circumstances:

- Embedded systems are **resource constrained**. Some debugging techniques might cause too much overhead (processing, communication and memory). Applying debugging may obscure the real problem (Heisenberg effect).
- The embedded processor is connected to **peripheral hardware components** such as A/D-converters, timers, communication interfaces, interrupt controllers and general purpose I/O pins. The embedded programm closely interacts with those components which makes it hard to trace.
- Embedded system often provide very **limited access** to the resources. If all you have is four LEDs, debugging will be very hard.

6.2 Tools

Good mechanics have many tools; you can't fix a car with just a hammer. Like good mechanics, good programmers need to be proficient with a variety of tools. Each has a place; each has a Heisenberg effect; each has power.[1]

Explanation *Simulator with source-level debugger*: A simulator allows for early debugging and execution of algorithmic code. It does not require any target hardware. A source-level debugger lets you step through your code, stop it, and then examine memory contents and program variables.

Explanation *In-circuit emulator (ICE) and JTAG debugger*: An Emulator *emulates* the behavior of the real chip. ICEs allow you to replace the real chip that interacts with I/O components for better insight. JTAG debuggers directly connect to the real chip instead of replacing it. ICEs and JTAG debuggers can be used for source-level debugging.

[1]The ten secrets of embedded debugging: http://www.embedded.com/showArticle.jhtml?articleID=47208538

Explanation *Simple printf statements*: This is perhaps the most flexible and primitive tool. Printing out variable values and function entry/exit points allows you to discover how your program is operating. Unfortunately `printf` is both clumsy to use (requiring code changes and recompiling) and quite intrusive because it greatly slows execution.

Explanation *Operating system monitors*: Operating system monitors display events, such as task switches, semaphore activity and interrupts.

Others: Profilers, memory testers, execution tracers, coverage testers.

6.3 Debugging Techniques for the BTnode

Following tools can be used to debug an AVR microcontroller. Some techniques require additional special hard- and software:

	Technique	**Hardware**	**Software**
1	Simulator	–	AVRStudio / AVaRICE + GDB / SimulAVR + GDB
2	ICE	ICE40/ICE50	AVRStudio
3	JTAG debugger	JTAGICE (mkII)	AVRStudio / AVR insight
4	printf	UART	Terminal
5	OS monitor	UART	Nut OS Tracer, Terminal

Optional Exercise 6.1. *Open the AVRStudio and consult the AVR Studio Tools and User Guide.*

1. *Compare the features and limitations of an Emulator (ICE50) with the ones of a JTAG debugger (JTAGICE).*

2. *What is on-chip-debugging (OCD)? Which hardware is required for OCD on the BTnode?*

3. *What happens with the peripheral components of the μC (UART, Timers, A/D Converter) when you enter stop-mode for source-level debugging (e.g. when a breakpoint is hit)?*

Optional Exercise 6.2. *Consider following table. Which tool(s) is/are most appropriate, in your opinion, for the given problems? Sometimes all tools can be applied in order find and fix a bug. Some with more, others with less effort. Justify your answer.*

Problem	***Tool:*** *Simulator/ JTAGICE/printf*	***Reason***
An algorithm that operates from memory to memory does not behave as expected.		
The μC communicates over one of its hardware UART with the Bluetooth module. In general, the μC sends a command sequence and parses the reply from the module. The implementation of this protocol on the μC is erroneous and needs debugging...		
You are implementing a network stack. A series of function is called (for each network layer) to process an incoming packet. In your current implementation, when a packet is received, the μC freezes somewhere in the processing. You want to find out where.		

6.4 AVR Simulation

In this section you will learn how to use AVR simulation for prototyping and source-level debugging. We introduce two simulators: *simulavr* and the *AVR Studio Simulator*. Unfortunately, both of them are quite limited, i.e. they only simulate a subset of the AVR peripherals (timers, etc.). As a consequence, applications that use Nut/OS can not be simulated. The simulator usually breaks in one of the timer interrupt routines.

Exercise 6.3. ***Simulavr + AVR-Insight*** *In this exercise you will learn how to start* simulavr *and how to connect the AVR-Insight debugger to it.*

1. *Create a new C file* `simpleio.c` *with the following code:*

   ```
   #include <io.h>

   void delay(void){
           int i;
           for(i = 0; i < 1000; i++);
   }

   int main(void){
           DDRF |= _BV(0);
           for(;;){
                   PORTF |= _BV(0);
                   delay();
                   PORTF &= _BV(0);
                   delay();
           }
   }
   ```

2. *Compile the file manually with the debug-symbols option (-g):*
   `avr-gcc -mmcu=atmega128 -g -I/usr/pack/btnode-1.0-mo/avr/include/avr simpleio.c -o simpleio.elf`

3. *Start AVR-Insight:*
   `avr-insight&`

4. *Start* simulavr *as a* gdb-server*:*
   `simulavr -g -d atmega128`
   The simulator should print out something like: `Waiting on port 1212 for gdb client to connect...`

5. *In order to connect Insight with the simulator, open the gdb-console (View→Console) and enter following commands:*

   ```
   file simpleio.elf
   target remote localhost:1212
   load
   break main
   continue
   ```

6. *Congratulations: now you can step through your code, set breakpoints and watches.*

Optional Exercise 6.4. ***AVR Studio Simulator***

1. *AVR Studio needs a different debug format. Compile the code from the last exercise with* `-gdwarf-2`*.*

2. *Open AVRStudio and open your* `.elf` *file from the* `File->Open File` *menu. A project wizard appears. Select* AVR Simulator *as debug platform and* ATmega128 *as device.*

3. *The simulator initializes and stops at the first instruction. Go to the* `AVR Simulator Options` *from the* `Debug` *menu, and set the frequency to* 8.00 *MHz.*

4. *In the I/O workspace window on the left side you find all the simulated resources of the AVR. Take some time to browse through the individual items. Expand the* `PORTF` *item.*

5. *Congratulations: now you can step through your code (F10), set breakpoints and watch how the ports and registers change in the workspace.*

Optional Exercise 6.5. ***Profiling printf with AVR-Studio***
Printf statements are often used for debugging. Printing out variable values and function entry/exit points allows you to discover how your program is operating. In this exercise we measure the cycle count of an example printf statement in order to get the feeling of the overhead.

1. *Edit your "*`nutsim.c`*" file:*

```
#include <io.h>
#include <stdio.h>
#include <dev/usartavr.h>
#include <hardware/btn-hardware.h>

int main(void) {
    u_long baud = 57600;

    btn_hardware_init();
    NutRegisterDevice(&APP_UART, 0, 0);
    freopen(APP_UART.dev_name, "w", stdout);
    _ioctl(_fileno(stdout), UART_SETSPEED, &baud);

    printf("UART baudrate = 57600\n");

    for(;;);
}
```

2. *Recompile the* `.elf` *file. The simulator should automatically restart and load the new file.*

3. *Step through the code until the yellow arrow is on the printf statement. Expand the processor item in the I/O workspace. Remember the cycle count.*

4. *Proceed one step (step over). Compare the cycle counter with the previous values. How many cycles did it take?*

5. *Normally printf statements have formatted output. Replace the existing printf statement with:*

```
printf("UART baudrate = %u,%u kbaud\n",
       (int)(baud / 1000UL),
       (int)((baud - (baud / 1000UL)*1000UL)/100));
```

6. *Compare the cycle count of the formatted printf with the unformatted one.*

6.5 The OS-Tracer

Printf is often used for debugging. However, in the previous section, we have seen that this method has a relatively large overhead. Thus, it is not suitable for tracing frequent events such as interrupts or thread switches. For such events, the *tracer tool* is more appropriate.

Explanation *Tracer Tool, Interactive Mode*: The tracer tool stores information about important OS events in memory and prints this information later on the terminal for analysis purposes. Important OS events include thread switches (due to sleeps, yields, priority changes, etc.) and interrupts. In addition to the type of event, the exact system time (microsecond resolution) and additional information (e.g. which thread did a sleep) is stored.
The tracer tool can be used in various different ways. The most simple is the interactive terminal mode. To activate the tool, use

```
#include <sys/tracer.h>
    btn_terminal_register_cmd("trace",NutTraceTerminal)
```

as it has been explained in the previous section.

Preparation *The current version of the btnut binaries does not flag OS events for the tracer. Therefore the sources have to be recompiled with the* `-DNUTTRACER` *option.*

1. *Open the file* `Makedefs` *located in the folder* `btnut`
2. *Uncomment the line* `DEFS.BTNODE3 += -DNUTTRACER`.
3. *Recompile the sources (*`make clean install` *in folder* `btnut`*).*

Exercise 6.6. *This exercise is a step-by-step tutorial for using the trace tool. First write a program that starts the LED thread, then registers the* trace *terminal command and then starts the terminal thread. Run this program and continue as follows:*

1. *Type* `trace`*, you will get the output:*

```
[es-ex3]$trace
 TRACE STATUS
 Mode is OFF
 Size is 0
 contains 0 elements
SYNTAX: trace [print [<size>]|oneshot|circular|size
<size>|stop|mask [<tag>]]
```

2. *Type* `trace oneshot` *and then type* `trace` *again. If you have not waited too long between the two commands, you will get something like this:*

```
[es-ex3]$trace oneshot TRACE mode ONESHOT, restarted
[es-ex3]$trace TRACE STATUS
 Mode is ONESHOT
 Size is 500
 contains 77 elements
SYNTAX: trace [print [<size>]|oneshot|circular|size
<size>|stop|mask [<tag>]]
```

Typing `trace` *again will give you a similar status except that the* `contains XX elements` *shows an increasing number. When it has reached* 500*, the* `Mode` *changes to* `OFF` *again as it was before we typed* `trace oneshot`*, but now* `contains 0 elements` *is replaced by* `is full`.

```
[es-ex3]$trace TRACE STATUS
 Mode is OFF
 Size is 500
 is full
SYNTAX: trace [print [<size>]|oneshot|circular|size
<size>|stop|mask [<tag>]]
```

3. *In the previous step, we have filled the trace buffer with events. We now can have a look at them by typing* `trace print 10`*, which gives you an output like this:*

```
[es-ex3]$trace print 10

TRACE contains 500 items,  printing 10 items. TAG
PC/Info      Time [s:ms:us]
----------------------------------------------
```

```
Thread Yield          idle         13:524:336 Thread Sleep
LED          13:524:604 Thread Yield          idle
13:581:857 Thread Sleep          LED          13:582:125 Thread
Yield          idle          13:639:392 Thread Sleep          LED
13:639:659 Thread Yield          idle          13:696:909 Thread
Sleep          LED          13:697:205 Thread Yield          idle
13:754:442 Thread Sleep          LED          13:754:710
```

In the `TAG` *column, you see the type of the recorded events. In the case shown above, all events are of type* `Thread Yield` *or* `Thread Sleep`*, the column* `Info` *shows you the name of the thread which has done a sleep or a yield and the* `Time` *column indicates at what time this was done. The time is* 0 *when the BTnode is booted.*

4. *The list of events does not allow you to quickly understand what is really going on. Therefore we now use the terminal program on the host computer to capture the terminal output in a file. Then we postprocess the trace file we have created in the previous step using Matlab. Thus start Matlab now. Type* `show_trace('<the filename of the captured terminal output>')`*, which opens a figure like the one shown in Fig. 6.1. Be sure to use a separate log file for each trace captured. In this figure, you can see time on x-axis and three threads on the y-axis.*

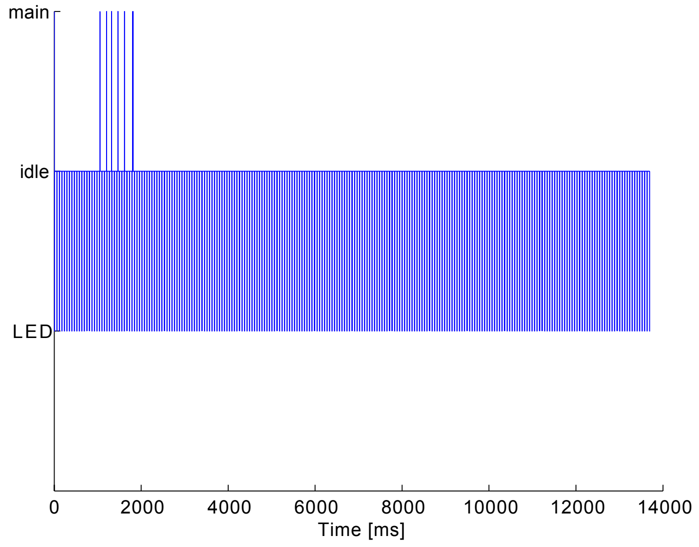


Figure 6.1: Execution of threads for the program listed in Exercise 6.6.

What you can see is that the BTnode spends most of the time in the idle thread. Periodically, it switches to the LED thread and a few times, the main thread was active. The LED thread is responsible for the periodic blinking of the LEDs, it becomes active approximately every 60ms *and takes about* 300μs *to execute. The main thread is responsible for capturing terminal input and launching the corresponding commands. Thus if you did not type* `trace` *while the buffer was filling, you will see only one spike to the main line at the very beginning of the trace. Otherwise (as shown in Fig. 6.1) you can see a spike for every letter of* `trace` *plus one when you pressed return. Parsing a keystroke takes about* 600μs*, executing the command after pressing enter takes much longer, approximately* 6ms. *When looking closely at the last spike, you may note that it actually consists of several spikes. This is due to the fact, that the* `trace` *command prints the status of the trace buffer to the terminal, but cannot do so in a single shot. It fills the UART buffer until it is full, then yields execution to the idle thread and is woken up when the buffer has become empty again to write the rest of the output.*

5. *In the previous step we have seen, that even when the BTnode seems to do nothing really useful, several threads are executed. To understand a little bit better how this actually works, we now do another trace capturing in addition to the threads also the occurrence of interrupts. To this purpose type* `trace mask`.

```
[es-ex3]$trace mask TRACEMASK
```

```
0 Critical  Enter OFF
1 Critical  Exit OFF
2 Thread    Yield ON
3 Thread    SetPrio ON
4 Thread    Wait ON
5 Thread    Sleep ON
6 Interrupt Enter OFF
7 Interrupt Exit OFF
8 Trace Start ON
9 Trace Stop ON
10 User * ON
```

You get a numbered list of event types followed by either `ON` *or* `OFF`*. Typing* `trace mask 6` *redisplays this list, but now the event type 6, which is the begin of an interrupt service routine is set to* `ON`*. Repeat this for the event type 7. Now take a trace as explained in the previous steps, capture the event list in a file and display it using Matlab.*

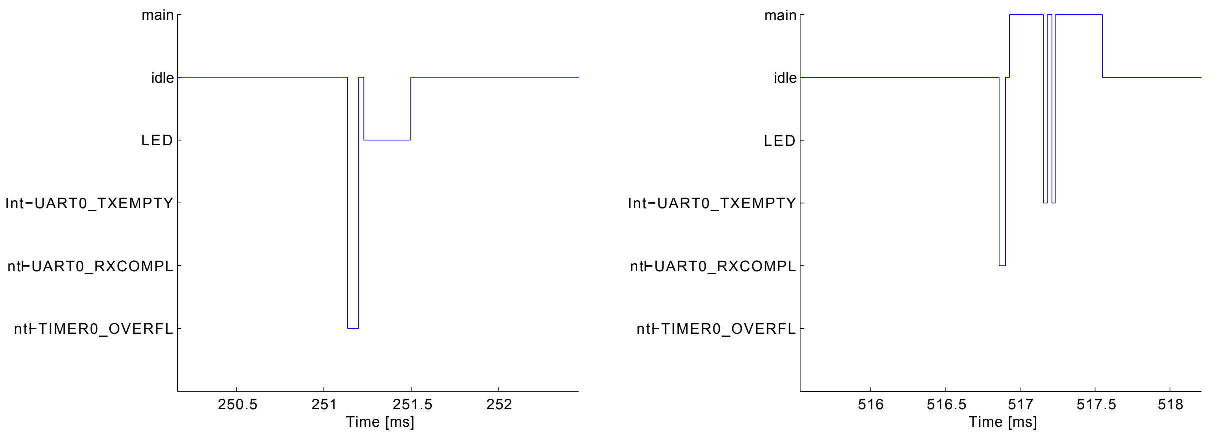


Figure 6.2: LED thread woken up by the timer interrupt. *Left:* LED thread woken up by the timer interrupt. *Right:* Main thread woken up by UART receive interrupt, causing transmit complete interrupts by echoing the terminal input.

Looking at Fig. 6.2, left side, you can see how the LED thread is triggered by the timer interrupt (`Int_TIMER0_OVERFL`*). On the right side of Fig. 6.2, it is shown that the main thread is activated after the occurrence of a UART receive interrupt (*`Int_UART0_TXCOMPL`*). Since the main thread echoes all received characters to the terminal, two UART transmit complete interrupts occur immediately after the activation of the main thread.*

Exercise 6.7. *The traces captured in the previous example show that most of the time is spent in a thread called* `idle`*, which was not started by our program. What is the purpose of this thread?*

Exercise 6.8. *When the tracing of interrupts is enabled, you can see timer interrupts. You can also see that a thread that sleeps always awakes immediately after these timer interrupts. Figure out the interval of these timer interrupts and think about what kind of restriction this implies for the* `NutSleep` *function.* **HINT:** *Remember that you can specify the sleep time in milliseconds.*

Explanation *Tracing a Particular Piece of Code*: The interactive mode of the tracer tool is very simple to use but it does not allow to trace a particular piece of code in which you are interested. To do this, it has to be used in a different way.
You may be interested in what a particular function call does. Therefore you would like to start tracing immediately before this function is executed. You can do this as shown here:

```
#include <sys/tracer.h>

int main(void) {

    // initializations
    NutTraceMaskSet(TRACE_TAG_INTERRUPT_ENTER);
    NutTraceMaskSet(TRACE_TAG_INTERRUPT_EXIT);

    // some code

    NutTraceInit(1000,TRACE_MODE_ONESHOT);
    // code you want to trace

    // some code
}
```

At the begin of the main routine you set the trace mask using the functions `NutTraceMaskSet` and `NutTraceMaskClear`. You find the macros that describe the types of events you want to trace in the `sys/tracer.h` header file. Then you start the trace using `NutTraceInit` immediately before the code you are interested in. The first parameter of this function determines the amount of items that are traced, the second parameter specifies whether tracing should be stopped when the trace buffer is full (`TRACE_MODE_ONESHOT`), or whether it should continuously overwrite the entries (`TRACE_MODE_CIRCULAR`), until tracing is stopped explicitly. The program shown above now automatically fills the trace buffer. You can either print it using the *trace* terminal command, or using the function `NutTracePrint`, which takes a single argument that determines how many trace entries shall be printed. If this argument is 0, the whole buffer is printed.

Exercise 6.9. *Trace the* `printf` *function. First use a string that is shorter than the length of the buffer (default is 64, may be changed using* `ioctl`*, see the avr-gcc manual for details), then a string that is longer. Enable the tracing of interrupts. Explain what you see.*

Chapter 7

Communication Using Bluetooth

7.1 Introduction

The Bluetooth technology is well suited to provide short-range wireless communications between electronic devices like e.g. mobile phones, laptops or PDAs. Without the need of a pre-established infrastructure, portable devices may create links and form Personal Area Networks (PANs).

This chapter addresses simple point-to-point communication between BTnodes. We will mainly concentrate on the interaction between the microcontroller and the Bluetooth radio and will – as far as possible – make use of pre-implemented data structures and functions of the BTNut system software. In doing so, the reader should gain some insight in the use of the thread/event-functionality of the Nut-OS and the low-level packet assembly routines provided by the BTnut API. To gain a certain confidence and understanding of Bluetooth communication, you can use the `bt-cmd` demo application.

We will have to familiarize the reader with certain details of the Bluetooth Specification [6]. In order to ease searching in the specification, all page numbers given in this tutorial refer to the page numbers of the PDF-document[1].

Section 7.2 presents the basic mechanisms that are used to access the Bluetooth radio capabilities. Therefore the interface between microcontroller and Bluetooth radio is explained. As an example, we take a closer look at the inquiry procedure used to discover other nearby Bluetooth devices. In Section 7.3 you will create wireless connections to other BTnodes and transmit short text messages.

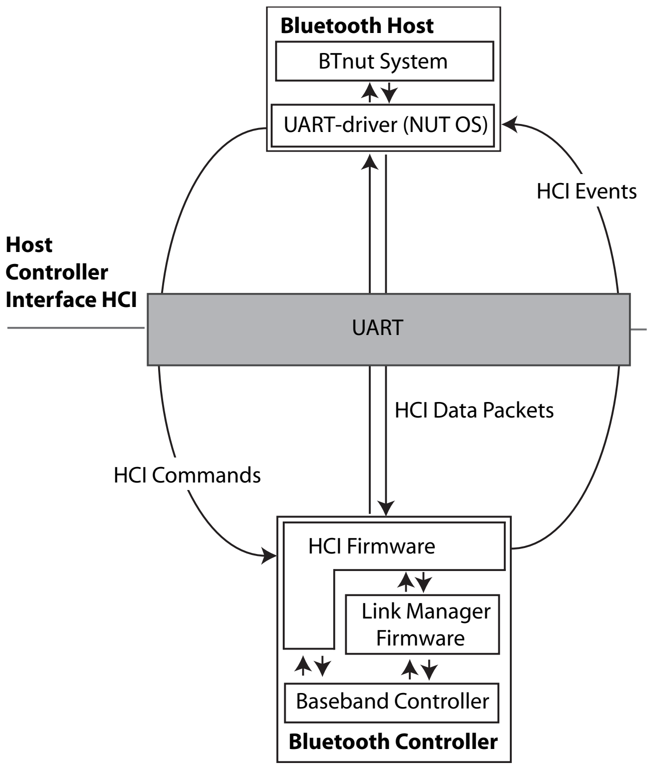
7.2 Discovery of Bluetooth devices

The Atmega128 microcontroller communicates with the Zeevo ZV4002 Bluetooth radio according to the principles defined in the *Host Controller Interface Functional Specification* [6].

In the following, we want to send an *Inquiry Command* to the Bluetooth controller. This command will cause the radio to enter inquiry mode and search for possible Bluetooth devices within communication range. The controller will count the total number of responding devices and collect a set of values for every single device. The value we are especially interested in is the *Bluetooth device address* of a discovered BTnode.

[1]We don't refer to the page numbers printed on the original document, since they are **not unique.**

Explanation *Host Controller Interface HCI*: As depicted, the Host Controller Interface defines signaling and data exchange between the so-called *Bluetooth host* and the *Bluetooth controller*. The Bluetooth host can be seen as the microcontroller running the BTnut system software and driving the NutOS UART-driver. The Bluetooth controller is physically connected to the host system via the UART. The Bluetooth controller is located on the Bluetooth radio and comprises the HCI firmware, the link manager firmware and the baseband controller. *HCI commands* can be sent from the host to the controller to initiate radio communication and access configuration parameters. On the other hand, the controller uses *HCI events* to inform the host when something occurs. Finally, *HCI data packets* may be transmitted in both directions.



Exercise 7.1. *Each Bluetooth device is characterized by a unique Bluetooth device address. Find the device address (MAC) of your BTnode. How many bytes are needed to represent a Bluetooth device address?*

A HCI packet is defined as shown below.

```
struct bt_hci_pkt_cmd {
        u_char type;
        u_char payload[255];
};
```

The `type`-parameter is needed to distinguish between command, event and data packets. For our purpose, we set `type=0x01` to define a command packet. The `payload`-array reserves 255 bytes for the actual command packet as specified on page 509f of the Bluetooth specification [6]. It starts with a 2 byte OpCode which is divided into two fields, called Opcode Group Field (OGF) and OpCode Command Field (OCF). Note that the bit ordering of the packet definition follows the *Little Endian* format, i.e. the LSB is the first bit sent over the UART.

Exercise 7.2. *Open the Bluetooth specification on page 510 to figure out how HCI Command Packets are constructed in general. You will find a detailed description of the Inquiry Command on pages 531 and 532. Figure out, what the single entries of the following* `bt_hci_pkt_cmd` *mean:*

```
    struct bt_hci_pkt_cmd pkt;
     pkt.type=0x01;
     pkt.payload[0]=0x01;
     pkt.payload[1]=0x04;
     pkt.payload[2]=0x05;
     pkt.payload[3]=0x33;
     pkt.payload[4]=0x8b;
     pkt.payload[5]=0x9e;
     pkt.payload[6]=0x05;
     pkt.payload[7]=0x05;
```

In particular, how long will this inquiry last and what is the maximum number of Bluetooth devices that can be found like this? **HINT:** *The general inquiry access code (GIAC) is 0x9E8B33 (see page 213 [6]).*

A function `inquiry` that sends an inquiry and displays the addresses of the found Bluetooth devices should look as follows: (Don't be confused if you are not familiar with all data types and functions – they will be explained later!)

```
struct btstack* stack;

void inquiry (u_char* arg){

//define a HCI command packet
struct bt_hci_pkt_cmd pkt;
// assemble the single bytes of the struct pkt (see previous exercise!)
// INSERT YOUR CODE HERE
// INSERT YOUR CODE HERE

// define a "command_response" structure
struct bt_hci_cmd_response wcmd;

//array for the storage of the answers of max. 10 devices
struct bt_hci_inquiry_result inquiry_result[10];

//initialize the cmd_response-structure
wcmd.ogfocf= ((0x01<<8)|(0x01<<2));
wcmd.cmd_handle= 0xFFFF;
wcmd.response=0;
wcmd.ptr= &inquiry_result;
wcmd.block=0;

//register the wcmd in the WaitQueue of the btstack
_bt_hci_setWaitQueue(stack,&wcmd);

//send the command packet ...
_bt_hci_send_pkt(stack,(u_char*)&pkt);

printf("Starting inquiry .....\n");
//wait for the inquiry to complete
// INSERT YOUR CODE HERE
// INSERT YOUR CODE HERE

printf("Inquiry done! \n");

// print inquiry_result[] to the terminal
// INSERT YOUR CODE HERE
// INSERT YOUR CODE HERE

}
```

First of all, we need a pointer to a variable of `struct btstack`-type for our function to work properly. This variable stores data for numerous devices, buffers and internal states. We need this structure for the definition of the UART-transport. Furthermore, the `btstack` structure stores a list of "signatures" of all uncompleted commands – or more precisely – a list of pointers to `bt_hci_com_response`-structures.

Explanation *struct bt_hci_cmd_response*:

```
struct bt_hci_cmd_response {
        u_short ogfocf;
        u_short cmd_handle;
        long response;
        void *ptr;
        HANDLE block;
};
```

The `ogfocf` is used to store the complete OpCode of the pending command. Setting the `cmd_handle` to 0xFFFF indicates that this command is not referring to an open baseband connection. When events return as a response to our Inquiry Command, the number of found devices will be stored in the component `long response`. The addresses of the found devices (together with several other values) will be stored at the location where the `void *ptr` is pointing. To indicate that our results are available, the `HANDLE block` will be #SIGNALED.

Explanation *struct inquiry_result*:

```
struct bt_hci_inquiry_result {
        bt_addr_t bdaddr;
        u_char page_scan_rep_mode :4;
        u_char page_scan_period_mode :4;
        u_long cod;
        u_short clock_offset;
        short rssi;
};
```

This struct stores all the collected data of one single discovered Bluetooth device. We are only interested in the `bt_addr_t`-component. As you already found out, the `bt_addr_t`-type is equivalent to a `u_char[6]`.

So we only send the Inquiry with the `_bt_hci_send_pkt`-function, pass an address to a `_bt_hci_setWaitQueue`-function and the result will be "automatically" stored in our prepared variables? Who is receiving and handling all the incoming events from the Bluetooth radio?

Answer: All the work is done by a THREAD called *"BTStack"*. This THREAD ...

- invokes a blocking `_bt_hci_get_pkt()`-function.
- searches for a matching `struct bt_hci_cmd_response` if an event arrives.
- dumps the payload of the event correctly.
- invokes a `EventPostAsync()` for the respective `HANDLE`.
- performs a final `NutThreadYield()`.

You should create the "BTStack"-THREAD in your main program by calling

```
stack = bt_hci_init(&BT_UART);
```

This function call simultaneously initializes the UART to the Bluetooth radio. Additonally, you should include the following header-files to ensure availability of all the functions and data types used so far:

```
#include <hardware/btn-hardware.h>
#include <terminal/btn-terminal.h>
#include <stdio.h>             // freopen
#include <dev/usartavr.h>      // NutRegisterDevice, APP_UART, UART_SETSPEED
#include <bt/bt_hci_dispatch.h> // for the setWaitQueue command
#include <sys/event.h>         // for NutEventWait
#include <bt/bt_hci_cmds.h>
```

Exercise 7.3. *Complete the* `inquiry` *function and register the command* `inquiry` *as a terminal command. Don't forget to initialize your hardware with* `btn_hardware_init()` *and* `btn_hardware_bt_on()`*. After having successfully implemented your Inquiry command, find out which BTnodes you have discovered!*

Exercise 7.4. *Use the OS-Tracer from Chapter 5 to trace your Inquiry command and see how the BTStack fetches the single events. You can start the tracer with* trace oneshot *and stop it with* trace stop*. Read on page 532 in [6] about which event packets may arrive at the Bluetooth host and identify those events in the trace plot.* **Hint:** *For this you will need to temporarily disable the LED thread.*

7.3 Creating Connections and Sending Data Packets

One of the parameters we send to the Bluetooth Controller with our Inquiry command was the *general inquiry access code* (GIAC). The Bluetooth Controller rearranges the Inquiry command packet in such a way, that the packet sent over the air begins with this GIAC. Actually, all transmissions over the physical channel *have* to begin with such an access code.

With the reception of a Bluetooth address we gained some knowledge that we can exploit to access the channel once more and create a connection to another device: We have to pass this address as a parameter to a "Create-Connection-command" which in turn causes the Bluetooth Controller to initiate the *Page procedure.* During this procedure, the Link Manager on the Bluetooth Controller tries to establish a link level connection to another device. Therefore, messages beginning with a *device access code* DAC are generated. The DAC is derived from the paged device's Bluetooth address.

Explanation *Terminal command* uartdebug: The terminal command `bt uartdebug 1` displays all HCI traffic on the UART. Bytes starting with a "w" are sent to the Bluetooth Controller, those starting with a "r" are received from the Controller. Events and Commands can be interpreted as follows:

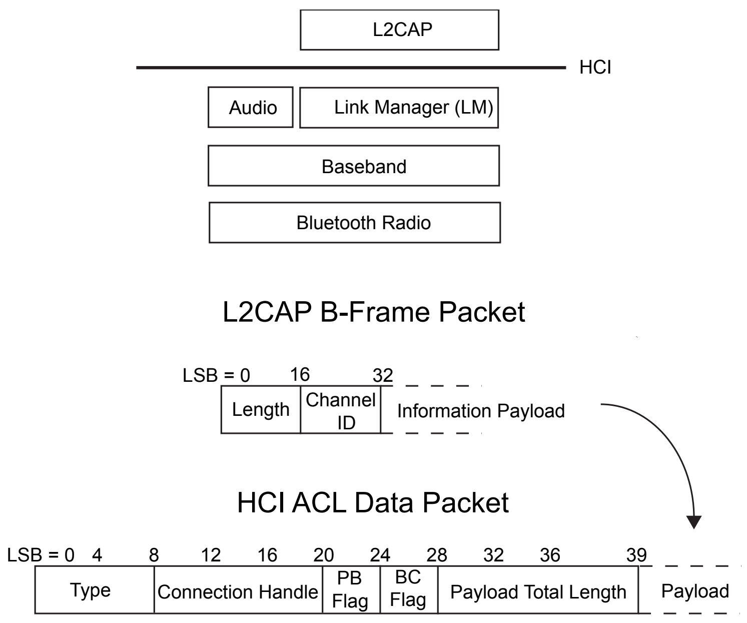
```
bytes                1  |     2      |       3       |       4       |     5
--------------------------------------------------------------------------------
HCI command packet:  1  |          Opcode          |parameterlength| parameter
HCI event   packet:  4  | event code |parameterlength| parameter
```

Exercise 7.5. *Compile and upload the* `bt-cmd` *application. Type* `bt uartdebug 1`*. Start an* `bt inquiry` *and create a new connection to an arbitrary BTnode using the command* `bt con`*. Identify the impinging events that are caused by the* `bt con`*-command! Analyze the received* `ConnectionCompleteEvent` *to figure out if we established a synchronous (SCO) or asynchronous (ACL) connection.* **Hint:** *HCI events are listed starting on page 695 [6] according to their Event Code.*

Now you should be connected with another BTnode i.e. both radios should be synchronized in terms of slot timing, frequency hopping sequence and access code to the physical channel. You can check your connections with the `contable`-command. As you see, a *connection handle* has been assigned to your connection. Those handles are used to identify connections between Bluetooth devices.

Once a connection is established, we want to send simple text messages to another BTnode.

Explanation *Logical Link Control and Adaptation Protocol L2CAP*: The Logical Link Control and Adaptation Protocol (L2CAP) resides directly above the Host Controller Interface (HCI). At the L2CAP layer, communication is based on so-called *channels*. This abstraction allows multiplexing and de-multiplexing of multiple channels over a shared link. Furthermore, L2CAP carries out segmentation and reassembly of application data for higher protocol layers. The figure shows a L2CAP basic information frame (B-frame) packet, starting with 2 bytes for the *length* of the information payload. Here, the length indicates the size of the payload in bytes. Bytes number 3 and 4 represent the *channel ID*. The rest of the packet is reserved for the actual payload. Clearly, the size of the payload is limited. But for the short messages we want to send in this tutorial we won't get into conflict with those payload limits.



Also an HCI asynchronous connection-oriented (ACL) data packet is illustrated. To distinguish between HCI commands, events and data packets, the *type* parameter has to be set. The *packet boundary* PB flag is used to indicate the first packet (PB=2) or a continuing fragment packet (PB=1) of a higher layer message. By setting the *broadcast flag* BC=0 a point-to-point message is defined. Finally, the payload length (again in bytes) concludes the header of the HCI ACL Packet. The body of the HCI ACL Packet consists of the L2CAP B-Frame Packet in our example. More information about L2CAP can be found in [6] on pages 963ff.

In the following, we want to write a `transmit` function which sends a HCI ACL Data packet of the form

```
u_char hci_acl_pkt[total_size];
  hci_acl_pkt[1]          =  ... ;
  hci_acl_pkt[2]          =  ... ;
              ...
  hci_acl_pkt[total_size] =  ... ;
```

We will send this packet using the function *bt_hci_send_acl_pkt* with the following signature:

```
bt_hci_send_acl_pkt(struct btstack *stack, u_short con_handle, u_char pb_flag,
       u_char bc_flag, u_short payload_total_length, struct bt_hci_pkt_acl *pkt);
```

As you can see, this function automatically sets the entries of the HCI ACL Packet header. However, it is still necessary to allocate memory (`total_size`) for all the entries of the `hci_acl_pkt`-packet, although the first entries don't have to be specified.

Exercise 7.6. *Copy the* `bt-cmd`*-application and add a new function called* `transmit`*. Register this function as a terminal command that takes a connection handle, a channel ID and a string-message as arguments. Define a* `hci_acl_pkt` *packet that allocates enough memory for a complete HCI ACL packet with an information payload of 20 characters and transmit it.* **Hint:** *You don't have to know any details about the* `bt_hci_pkt_acl` *-struct. Just cast your* `hci_acl_pkt` *packet accordingly!*

In order to receive short messages, the following `receive`-function has to be defined:

```
struct bt_hci_pkt_acl* receive(void *arg, struct bt_hci_pkt_acl *pkt,
                               bt_hci_con_handle_t con_handle,
                               u_char pb_flag, u_char bc_flag,
                               u_short len, u_long t_arrive)
{
        u_char* l2cap_hdr = pkt->payload;
        u_char* l2cap_data;
        u_short chan_id;

        chan_id = l2cap_hdr[2] | (l2cap_hdr[3] << 8);

        l2cap_data = &l2cap_hdr[4];

        printf("message received on channel %d: %s\n", chan_id, l2cap_data);
        return pkt;
}
```

If you now define the packet

```
u_char acl_pkt[120];
```

a register the `receive`-function as a callback

```
bt_hci_register_acl_cb(stack, receive, (struct bt_hci_pkt_acl*)acl_pkt, NULL);
```

messages sent to your BTnode will be displayed automatically on the terminal.

Exercise 7.7. *Test your* `transmit`*-function by sending a short message to a SUPERVISOR-node that uses a preloaded application. Use channel 65 for sending this message. If you have implemented everything corretly so far, you will receive an acknowledgment from the SUPERVISOR-node immediately.*

Optional Exercise 7.8. *Check if some of your neighbors have already finished exercise 7.7. Try to communicate with another group doing this tutorial. Optionally, try to combine commands from* `bt-cmd` *such as* `name`*,* `rname`*,* `role`*,* `roleset` *with* `transmit` *to get status information from other nodes.*

Chapter 8

Interfacing to Handheld Devices

8.1 Introduction

In addition to the regular BTnode hardware a cellular phone with a Bluetooth interface is required for successful completion of this tutorial.

Figure 8.1 shows an overview of the Bluetooth protocol stack. On top of the Host Controller Interface (HCI) and the Logical Link Control and Adaptation Layer Protocol (L2CAP) the Bluetooth stack provides the RFCOMM protocol which emulates a serial port connection. Over such a RFCOMM connection basic *Attention Commands* (AT Commands) can be sent to control a cell phone. The topic of this tutorial covers setting up an RFCOMM connection to a cell phone and sending AT Commands to make the phone dispatch an SMS message.

Learning target of this tutorial is familiarizing with the Bluetooth Protocol Stack and working with standard protocols.

8.2 RFCOMM

Bluetooth is a wireless communication service sending in the 2.4 GHz Band. It is based on a centralized network topology. Nodes communicating with each other form a piconet that consists of one master and at most 7 slaves. The master initiates the transmission and the slaves respond to it. To achieve robustness against interference Frequency Hopping is applied. Once every 0.625ms the frequency is changed. Therefore transmission is partitioned into time slots of 0.625ms length. Bluetooth specifies two types of transmission schemes that can be established between different devices.

Explanation *Synchronous Connection-Oriented (SCO)*: The SCO link provides a circuit-switched connection between the master and a single slave of the piconet. The service is symmetric and requires reservation of time slots at regular intervals. Therefore the master sends SCO packets at regular intervals. The specific SOC slave is allowed to respond in the subsequent time slot. SOC packets are never retransmitted therefore it is an unreliable service. It is mostly used for voice applications.

Explanation *Asynchronous Connection-Oriented (ACL)*: The ACL link provides a packet-switched connection between master and all active slaves of a piconet. A slave is only allowed to transmit an ACL packet if it has been polled by the master in the previous time slot. The ACL link uses a fast acknowledgment and retransmission scheme to guarantee reliability. Since no time slots are reserved for transmission, this type of communication is usually used for non time-critical applications.

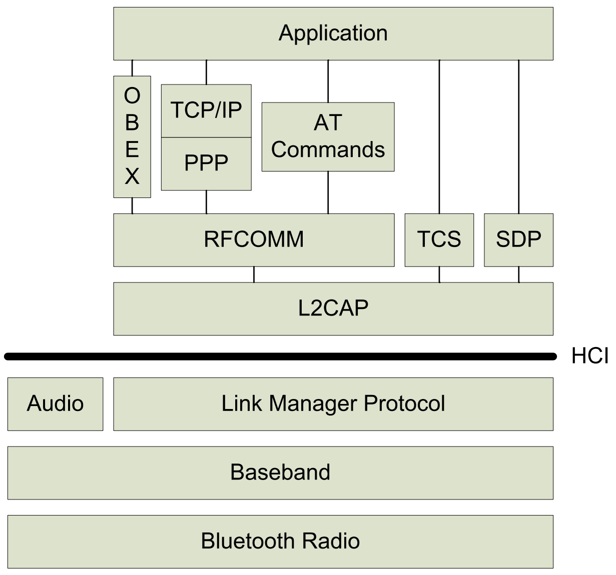


Figure 8.1: The Bluetooth Protocol Stack

The Logical Link Control And Adaption Protocol (L2CAP) has been discussed extensively in section 7.3. The focus of this tutorial is on the higher-level protocols and their application. As explained in section 7.3 the Bluetooth address is needed to establish a connection to a remote device.

Exercise 8.1. *Find out the Bluetooth device address of your cell phone. This can be done in two ways:*

- *Some manufacturers put a tag with the address printed on it on the back of the phone where the battery is inserted. The address is 12 digits long, hexadecimal formatted and usually indicated by the term* BD ADDR.

- *As discussed in section 7.2 Bluetooth devices can be discovered using the* Inquiry Command. *The application* `bt-cmd` *located in the folder* `app/bt-cmd/` *provides all the necessary terminal commands to determine a device's Bluetooth address:*

  1. *Compile and burn the file* `bt-cmd.c`.
  2. *Turn on the Bluetooth radio of your cell phone and make the phone traceable. The two settings usually have to be turned on separately since this is a security mechanism to hide the phone's Bluetooth address.*
  3. *Open a terminal and start an inquiry. This will give you a couple of Bluetooth addresses.*

4. *Now you need to find out which address belongs to your phone. Use the command* `bt rname` *to read the name of a remote device. You can edit the name of your phone in the phone's Bluetooth setup. The way to do that depends on the phone's menu navigation. Some phones provide a separate menu item for* `Bluetooth` *others include it in* `Setup->Bluetooth` *or* `Connections->Bluetooth` *or a combination of them* `Setup->Connections->Bluetooth` *or even differently.*

Explanation *Radio Frequency Communication (RFCOMM)*: RFCOMM is a simple transport protocol that emulates a serial interface (RS232) over an L2CAP link. Up to 60 simultaneous connections between two Bluetooth devices are supported.

Explanation *Pairing*: Pairing is a security mechanism built into Bluetooth to prevent unauthorized connections. At the first connection attempt, connection keys of 128bit length are generated out of the Bluetooth addresses of the devices and some random number. These keys are then stored for further interaction. To safely transmit the connection keys at this very first connection set up, an initializing key has to be generated which in turn is calculated out of some random number, one of the Bluetooth addresses and the Bluetooth PIN-code.
If for example a connection between two cell phones is being established, then first user A is asked to enter a PIN-code (can be arbitrary) to its phone. This code is then sent to B's phone. B is asked to enter a PIN-code as well which is sent back to A's phone. If the two PIN-codes match, then a trusted pair is formed.

Preparation *The current version of the btnut binaries is not compatible with connections to cell phones. Therefore a patch has to be applied to the sources.*

1. *Open the file* `bt_rfcomm.c` *located in the folder* `btnut/btnode/bt/`
2. *Search for* `case BT_RFCOMM_MSC_CMD` *and insert the instruction* `NutSleep(1);` *on the following line.*
3. *Compile the sources (*`make install`*).*

Exercise 8.2. *Establish an RFCOMM connection to your cell phone on channel* `1`*. For this purpose upload the demo application* `rfcomm-cmd` *to the BTnode. It is located in the folder* `app/rfcomm-cmd`*. The following terminal commands will be needed:*

- `rfsession` *opens a connection*
- `rfdiscon` *closes a connection*

To find out how to use the commands simply type the command and hit `Enter`*. This should show you the usage. Don't panic if an error occurs during connection setup. It is nothing unusual.* **HINT:** *During the pairing process, the BTnode sends the default hard coded PIN-code* `1234`*.*

Upon successfully creating the connection, the following line is printed to the terminal.

```
RFCOMM Connect on dlci 2...
```

At this point no more functionality is provided so just close the connection. **HINT:** *The connection handle* `DLCI` *of a connection on channel* `1` *is always* `2`*.*

If you have constant problems setting up the RFCOMM connection, use a longer sleep period in the preparation step e.g. `NutSleep(500)`*.*

The following functions from the `bt/bt_rfcomm.h` library have been used in the previous exercise to open and close an RFCOMM connection. They will be needed in exercise 8.3.

Explanation *bt_ rfcomm_ start_ session*:

```
u_char bt_rfcomm_start_session(bt_addr_t bt_addr, u_char page_scan_rep_mode,
                               u_short clock_offset);
```

This function opens an L2CAP channel to a remote device if it has not been opened yet.
The argument `bt_addr` is the Bluetooth address of the remote device. For the other two arguments a `0` can be passed on to the function if no other knowledge available.
The function returns `0x00` if channel set up was successful.

Explanation *bt_ rfcomm_ connect*:

```
u_char bt_rfcomm_connect(u_char channel_nr, BT_RFCOMM_CON_CB, BT_RFCOMM_RCV_CB,
                         BT_RFCOMM_LINE_CB, BT_RFCOMM_CREDIT_CB, u_char credit_limit,
                         void *cb_arg)
```

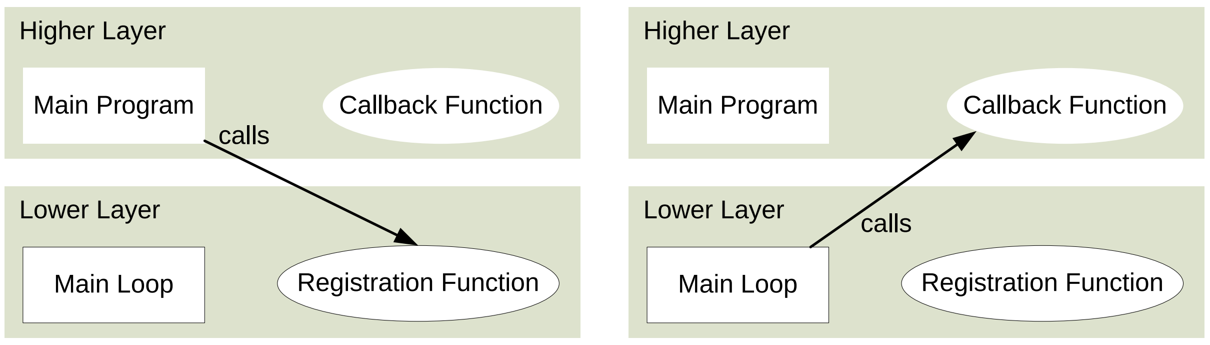
This function establishes an RFCOMM connection on the channel specified by `channel_nr`. `BT_RFCOMM_CON_CB`, `BT_RFCOMM_RCV_CB`, `BT_RFCOMM_LINE_CB` and `BT_RFCOMM_CREDIT_CB` are callback functions. Use the value `10` for `credit_limit` and the `NULL` pointer for the callback argument `cb_arg`.
The function returns `0x00` if connection set up was successful.

Explanation *bt_ rfcomm_ disconnect*:

```
u_char bt_rfcomm_disconnect (u_char dlci)
```

This function closes an RFCOMM connection. It expects the connection handle `dlci` as argument and returns `0x00` if the connection was successfully closed.

Explanation *Callback Function*: Callback functions are often used in protocol programming. The higher layer calls a lower layer function passing a function pointer as argument to it. This allows the lower layer to execute a function that is defined on a higher layer.



8.3 AT Commands

At the end of this section you will be able to send SMS messages from the BTnode. As shown in section 8.2 an RFCOMM connection can be established between a BTnode and a cell phone. Over this link, *Attention Commands* (AT Commands) can be sent (see the Bluetooth stack, figure 8.1).

Explanation *AT Commands*:
Originally, the AT Commands were developed as a specific programming language for dialup modems. Back in the early days of Microprocessors when the Apple II was booming, users had to dial the phone manually and use an acoustic coupler for modem connection. Although internal modems did not have this shortage, they lacked the ability of being universal, since a different hardware design was needed for every computer bus. A more modular approach was an external modem connected to the widely available RS232 interface. It was then, when Dale Heatherington came up with the trailblazing idea to develop an external modem that was able to receive commands over the RS232 data line. Hence the Hayes Command Set or AT Commands were created.
Mobile phone manufacturers in one way or another have adopted this command set for the built-in modems. Those modems can be accessed via Bluetooth, Infrared, USB cable or RS232 cable connection. Most of a cell phone's basic functionality AT Commands e.g. sending an SMS message are specified in [5] and standards referenced in there. However there are also vendor specific commands.
The standard AT Command format consists of the Command itself followed by a carriage return. Four different types of commands exist [14]:

The Set Format It is used to change settings of the mobile phone.

AT<command>=<parameters>**<CR>**

where	AT	notifies the built-in modem that a command is being entered
	<command>	the name of the command being entered
	<parameters>	the values to be used by the command
	<CR>	the carriage return `"\r"`

The Execute Format It is similar to the Set Format but the Execute Format usually does not require any parameters and is used to obtain information about the mobile phone.

The Read Format It is used to read current settings.

AT<command>?<CR>

Command Help Checks whether the command is available and returns the range of the parameters.

AT<command>=?<CR>

However some commands such as the send SMS command require a special line delimiter.

As mentioned in the explanation, AT Commands can be treated just like data packets that have to be sent over an RFCOMM channel. Therefore the following function can be used.

Explanation *bt_ rfcomm_ send*:

```
u_char bt_rfcomm_send (u_char dlci, u_char *data, u_short length)
```

This function sends data over an existing RFCOMM channel. It expects the connection handle `dlci`, the data packet and its length as arguments and returns `0x00` if the sending process was successful.

Exercise 8.3. *The goal of this exercise is to send some basic AT Commands from a BTnode to a cell phone.*

1. *Create a new source file and insert the contents of the* `rfcomm-cmd` *application that you used in the previous exercise. command registration function calls at the end of the file, as they won't be needed.*

*Also delete the three command initialization function calls (*bt, l2cap *and* rfcomm*) located just above the registration function calls.*

2. *Insert the callback function definitions and the other lines printed below.*

3.
```
#define MIN_CREDITS 10
#define MAX_CREDITS 40

void rcv_cb(u_char dlci, u_char * payload, u_short len, void *arg)
{
    u_short idx;
    if (len > 0) {
        printf("\n");
        for (idx = 0; idx < len; idx++)
            printf("%c ", payload[idx]);
    }
}

void con_cb(u_char dlci, u_char type, void *arg)
{
    if (type == BT_RFCOMM_CONNECT) {
        printf("RFCOMM Connect on dlci %d...\n", dlci);
        bt_rfcomm_send_credits(dlci, MAX_CREDITS - BT_RFCOMM_DEF_CREDITS);
    } else {
        printf("RFCOMM Disconnect on dlci %d...\n", dlci);
    }
}

void line_cb(u_char dlci, u_char flags, void *arg)
{
    printf("rfcomm Line status has changed: dlci: %d, flags: %02x\n", dlci, flags);
}

void credit_cb(u_char dlci, u_char credits, void *arg)
{
    printf("rfcomm Credits running low for dlci %d. Credits remaining: %d\n", dlci, credits);
    printf("rfcomm Send new credits: %d\n", MAX_CREDITS - credits);
    bt_rfcomm_send_credits(dlci, MAX_CREDITS - credits);
}
```

4. *Write a function that opens a RFCOMM connection to a cell phone on RFCOMM channel* `1` *using the* `bt_rfcomm_start_session` *and* `bt_rfcomm_connect` *functions. Include some delay after each function call, e.g.* `NutSleep(1000)`. **HINT:** *For the callback arguments pass the names of the copied functions.*

   Afterwards send some general AT Commands (see below) and close the RFCOMM connections using the function `bt_rfcomm_send` *in the former and the function* `bt_rfcomm_disconnect` *in the latter case. Parameter of the function should be the Bluetooth address.* **HINT:** *Include some delay after each AT Command, e.g.* `NutSleep(1000)`.

   Register this function as a terminal command. **HINT:** *Registering terminal commands has been introduced in section 4.3. Besides, it is documented in the header file* `btn-terminal.h`*, which can be looked up in the BTnut API.*

`AT`	*Determines the presence of a phone. Returns either* `OK` *or* `ERROR`.
`AT+CGMI`	*Request Manufacturer Identification*
`AT+CGMM`	*Request Model Identification*
`AT+CGSN`	*Request Product Serial Number Identification*

5. *Compile and upload your program. Open a terminal to observe the output.*

8.4 Sending an SMS Message using AT Commands

There are two ways to ways to send SMS messages using the AT Commands. On the one hand, there is the simple SMS text mode [11] where you can send the message as plain text:

1.	`AT+CMGF=1`	Set to text mode.
2.	`AT+CMGS="<phone number>"`	Send the recipient's phone number in international format i.e. +41...
3.	`<message>`	Send the message followed by the special line delimiter defined as `0x1A` in the ASCII code.

On the other hand, there is the more complicated protocol data unit (PDU) mode. Since the text mode is not supported by every phone, this tutorial only focuses on the PDU mode. The PDU for SMS messaging is assembled as follows.

```
00 25 00 0B 91 14 77 14 36 21 F6 00 00 1A 47 79 B9 4C 4F BB CF 73 90 59 FE 6E 83 E8 E8 32 48 48 75 BF C9 65 17
```

- length of the SMS-carrier address: `00` selects the number stored on the phone's SIM card.
- message flags: use `25`
- message reference number: `00` lets the phone set the reference number.
- length of the destination address (number of digits in hex format): `0B`
- format of the destination address: use `91` for international format i.e. `+41`...
- destination address: each digit of the phone number represents half of a Byte. Therefore if the length of the phone number is odd, a trailing `F` has to be added to complete the last Byte. The destination address is generated out of the phone number by flipping every Byte's lower and upper half. So the destination address from the example represents the phone number `41774163126`. The `+` sign is omitted.
- protocol identifier: use `00`
- data coding scheme: use `00`
- length of the original message: this is the number of characters (at most 160) of the message string including spaces in hex format.
- encoded message: the original message is coded using a 7bit ASCII character set. The stream of 7bit characters is then encoded into a Byte stream to form the encoded message. The coding scheme is depicted in the following formalism.

Definitions

length of message string	n
element of message string	$k, \quad 0 \le k \le n-1$
character k	$\mathbf{X} = X_6 \dots X_0$
character $k+1$	$\mathbf{Y} = Y_6 \dots Y_0$

Encoding

`if` $(k+1) \bmod 8 \neq 0$

$$\underbrace{\underbrace{Y_{k \bmod 8} \dots Y_0}_{k \bmod 8+1[\text{bit}]}\underbrace{X_6 \dots X_{k \bmod 8}}_{7-k \bmod 8[\text{bit}]}}_{1\text{Byte}}$$

`else` `NULL`

Using this coding scheme on the message “Greetings from the BTnode.” should result in the Byte stream shown in the example.

The PDU is of type string i.e. address lengths for example have to be converted to hex strings. The message is sent in PDU mode using the following commands:

1.	`AT+CMGF=0`	Set to PDU mode (set by default).
2.	`AT+CMGS=<PDU length>`	Number of Bytes of the PDU minus one since the leading `0x00` does not count. In the example it were `AT+CMGS=36`.
3.	`<PDU>`	Send the PDU followed by the special line delimiter defined as `0x1A` in the ASCII code.

Optional Exercise 8.4. *In this exercise you are asked to implement the coding of the message as specified in the PDU mode. It is a difficult exercise. However such problems quite commonly have to be solved in embedded programming in order to comply with the different interfaces. Since this implementation is needed in the next exercise a sample solution is provided below.*
Add another function to your source file that implements the 7 to 8 bit ASCII encoding. It should take the message string and a pointer to an allocated array for the encoded string as input parameters.

```
int character_value(char character)
{
    const char alphabet[128] = {’@’, ’@’, ’$’, ’@’, ’@’, ’@’, ’@’, ’@’, ’@’, ’@’, ’\n’, ’@’, ’@’,
        ’\r’,’@’, ’@’,’@’, ’_’, ’@’, ’@’, ’@’, ’@’, ’@’,’@’, ’@’, ’@’, ’@’,’@’, ’@’, ’@’, ’@’,
        ’@’,’ ’, ’!’, ’"’, ’#’, ’@’, ’%’, ’&’, ’\’’, ’(’, ’)’,’*’, ’+’, ’,’, ’-’, ’.’, ’/’,
        ’0’, ’1’, ’2’, ’3’, ’4’, ’5’, ’6’, ’7’,’8’, ’9’, ’:’, ’;’, ’<’, ’=’, ’>’, ’?’, ’@’,
        ’A’, ’B’, ’C’, ’D’, ’E’, ’F’, ’G’, ’H’, ’I’, ’J’, ’K’, ’L’, ’M’, ’N’, ’O’, ’P’, ’Q’,
        ’R’, ’S’,’T’, ’U’, ’V’, ’W’, ’X’, ’Y’, ’Z’, ’@’, ’@’, ’@’, ’@’, ’@’, ’@’, ’a’,’b’,
        ’c’, ’d’, ’e’, ’f’, ’g’, ’h’, ’i’, ’j’, ’k’, ’l’, ’m’, ’n’, ’o’,’p’, ’q’, ’r’, ’s’,
        ’t’, ’u’, ’v’, ’w’, ’x’, ’y’, ’z’, ’@’, ’@’, ’@’,’@’, ’@’};
    int i;

    for(i=0;i<128;i++){
        if(character == alphabet[i]){
            return i;
        }
    }
    return -1;                              //no valid character
}

int bin2int(char * binary)
{
    int i;
    int sum = 0;
    int length;

    length = strlen(binary);
    for(i=0;i<length;i++){
        if(binary[i] == ’1’){
            //sum += (int)pow((double)2,(double)(length-1-i));
            sum += 0x01<<(length-1-i);
        }
    }
    return sum;
}

void process_message(char * message_str, char * message)
{
    char buffer[8]="\0";
    int length;
    int i;
    int character = -1;
    char base[8]="\0";
    char carry[8]="\0";
    char rdbuffer[8]="\0";

    //init
    message_str[0] = '\0';

    length = strlen(message);
    if(length<=15){
        strcat(message_str, "00000");
    } else {
        if(length>160){
            length = 160;
        }
        strcat(message_str, "0000");
    }
    itoa(length, buffer, 16);   //convert integer to hex string
    strcat(message_str, buffer);

    for(i=0;i<=length;i++){
        if(i == length){
            if(base[0] != '\0'){
                character = bin2int(base);
                itoa(character, base, 16);
                if(strlen(base)==1){
                    base[1]=base[0];
                    base[0]='0';
                    base[2]='\0';
                }
                strcat(message_str, base);
            }
            break;
        }
        character = character_value(message[i]);
        if(character != -1){
            strcpy(buffer,"0000000");
            itoa(character, rdbuffer, 2);
            strcpy(buffer+7-strlen(rdbuffer), rdbuffer);
            if(i != 0 && i%8 !=0){
                strncpy(carry, buffer+7-i%8, i%8);
                carry[i%8] = '\0';
                strcat(carry, base);
                character = bin2int(carry);
                itoa(character, carry, 16);
                if(strlen(carry)==1){
                    carry[1]=carry[0];
                    carry[0]='0';
                    carry[2]='\0';
                }
                strcat(message_str, carry);
                strncpy(base, buffer, 7-i%8);
                base[7-i%8] = '\0';
            } else{
                strcpy(base, buffer);
            }
        } else{
            //ERROR: Not a valid character
        }
    }
}
```

Exercise 8.5. *In this exercise you are asked to implement functionality to completely assemble a PDU of an SMS message and to send this PDU over RFCOMM to your cell phone.*

1. *Add another function to your source file. This function should take the recipient's phone number and the message string as input parameters.*
2. *In this function assemble the PDU. Use the function implemented in the previous optional exercise or the sample solution for message encoding.*
3. *Also insert the code for the necessary AT Commands to make the cell phone dispatch the SMS message. Insert a wait e.g.* `NutSleep(5000)` *after sending the PDU if you would like to observe the feedback from the phone.*
4. *Call this function in your code after you have created a connection to your cell phone.*

HINT: *These string operators can be useful:* `strlen`, `strcat` *and* `strcpy`. *Look up on the internet on how to use them.* **HINT 2:** *The standard library function* `itoa` *can be used to convert integer to string.* **HINT 3:** *Include the necessary libraries.*

Explanation *user_ input*:

```
u_char user_input( FILE* stream, u_char *buffer, u_char count);
```

This function reads user input from stream.
It stops after a newline or `count-1` characters have been read. The argument `stream` can for example be the terminal i.e. `stdout`. The parameter `buffer` is a pointer to a buffer where the input is received. It has to be allocated with enough space. The input is always null terminated.
The function returns the length of the input string in the buffer.

Optional Exercise 8.6. *Create a simple user interface to input the message and recipient's phone number and if desired the Bluetooth address of the sending phone through the terminal. Use the* `user_input` *function.*

Chapter 9

The Chipcon Radio

9.1 Introduction

The BTnode features a Chipcon CC1000 radio module – the same radio that is used in the popular MICA mote platform, allowing those two platforms to communicate over a common radio channel. In contrast to the Bluetooth radio module (which was covered in the previous section), the CC1000 is very simple: you can either send a radio signal, or listen for incoming signals from other nodes. As there is no automatic frequency hopping as in Bluetooth, we neither have discovery phases nor master-slave relationships. There is no default packet format or standardized access interface (like HCI or L2CAP) – using simple commands like "turn radio on" and "send this data", we can pretty much send out anything we please. However, this newfound freedom also comes at a price: Without the complex Bluetooth synchronization, we will need to take care of limiting access to the shared broadcast medium (i.e., the radio channel) ourselves. Otherwise, if two or more nodes in range of each other decide to send at the same time, their signals will interfere with each other (this is called a "collision") and none of the sent data can be received.[1]

Regulating access to a shared communication medium is done by a "medium access control" (MAC) layer.[2] The MAC layer is responsible for deciding who gets access to the physical layer at any one time. It also detects transmission errors and provides addressing capabilities, i.e., it verifies whether a received packet was actually intended for the receiving station. BTnut comes with one particular MAC-layer implementation for its Chipcon radio, based on Berkeley's B-MAC protocol [12]. The B-MAC protocol offers a very energy efficient way of regulating medium access, which is especially suited for sensor networks, called *clear channel assignment* (CCA). It also offers an equally low-power oriented approach to listening for incoming data, called *low power listening* (LPL). Just as any other MAC protocol, B-MAC detects transmission errors for us, handles acknowledgements, and provides an addressing scheme. Overall, however, B-MAC is a rather simple protocol that minimizes protocol overhead while providing essential support for low-power communication.[3]

9.2 Accessing the CC1000

Three main modules (and a number of helper modules)[4] implement control of the CC1000 radio on our BTnode. The low-level access to the radio (i.e., the physical layer) resides in `cc1000.c`, the B-MAC protocol (the data-link layer) is implemented in `bmac.c`, and the high-level routines for sending and receiving data are in `ccc.c`. This modular setup allows the use of multiple MAC protocols, though so far only a single one is available. Figure 9.1 gives an overview of the dependencies. Unless you want to program your own

[1]Note that they don't even have to be in range of each other, if a third, receiving node "sees" both of them. This is known as the *hidden terminal problem.*

[2]In the ISO/OSI network reference model, the physical layer (layer one) would be our Chipcon radio, while the MAC would be situated in layer two, the data link layer.

[3]Its authors explicitly encourage the implementation of more sophisticated MAC protocols on top of B-MAC [12].

[4]Specifically, the B-MAC protocol uses `cca.c` to implement the clear channel assignment, while `crc.c` provides CRC error checking. Additionally, `cc1000_tuner.c` allows us to change the radio's frequency.

MAC-layer, you will only need to include both `ccc.h` and `bmac.h`. The next three sections will explain initialization the radio, sending data, and receiving data.

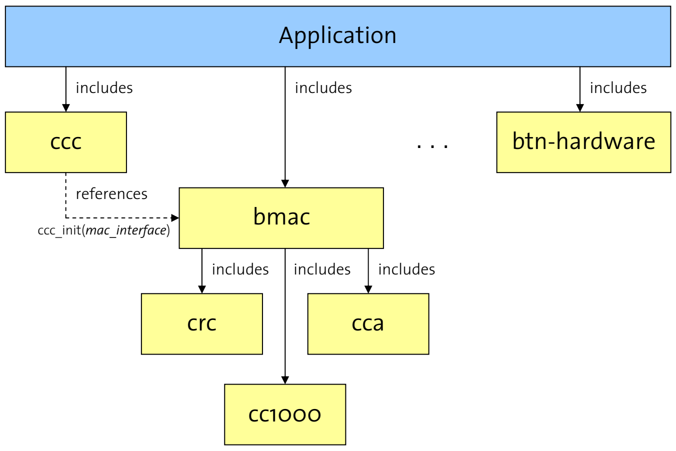


Figure 9.1: CC1000 Modules.

9.2.1 Initialization

Initializing the CC1000 radio is done in the `ccc_init` function, which takes as its single argument a *mac_ interface* structure, i.e., a reference to a MAC protocol to be used for communication. Consequently, we will first need to initialize our MAC library, which will create a matching instance of such a *mac_ interface* structure for us. The relevant code thus looks like this:

```
#include <cc/bmac.h>
#include <cc/ccc.h>

#define NODE_ADDRESS 0x0000;

static void init_radio (void) {
    int res;
    /* initialize bmac -- also fills bmac_interface structure */
    res = bmac_init(NODE_ADDRESS);
    if (res != 0) { /* bmac initialization failed - halt system */ }
    bmac_enable_led(1);
    res = ccc_init(&bmac_interface);
    if (res != 0) { /* cc1000 initialization failed - halt system */ }
}
```

Notice that we need to supply a node address for B-MAC initialization. This address will be used by the MAC layer to filter out packets addressed to other nodes, i.e., we will only receive packets addressed either directly to this node, or those sent to a broadcast address. More details about addresses can be found below.

The `bmac_enable_led` command activates LED feedback for sending and receiving, i.e., the B-MAC layer will light the green (outermost) LED when listening, the blue (innermost) LED when sending or receiving, and the red LED in case of CRC errors.

Exercise 9.1. *Write a program that activates the CC1000 as described above, including the B-MAC LED activation, before going in an endless* `NutSleep`*. What do you observe? Add terminal access to your application and integrate the Nut/OS command set (using* `nut_cmds_register_cmds`*). Check the output of the* `nut threads` *command.*

9.2.2 Sending Data

Once we have initialized the radio, we can use the `ccc_send` command (part of *ccc.h*) to send out data.

```
#define MAX_PACKET_SIZE 8
#define PACKET_TYPE 0x01        /* application-specific, 0-255 */

pkt = new_ccc_packet(MAX_PACKET_SIZE);

void _cmd_send_ushort(char* arg) {
    int val;
    pkt->length = 4;

    if (sscanf(arg,"%u",&val)==1) {
        sprintf(pkt->data,"%u", val));
        if (ccc_send(BROADCAST_ADDR, PACKET_TYPE, pkt)) {
            /* send failed (<> 0 indicates error) */
        }
    }
}
```

`ccc_send` takes as input the intended receiver's address, the type of packet that should be sent, and the packet itself. Packets not only contain payload, but also source and destination information, an explicit size (`length`), as well as a *packet type.* We can use the `new_ccc_packet` function to obtain a pointer to an empty packet struct, with memory allocated up to the given size (`PACKET_SIZE` in our example code above). However, we still need to explicit specify the actual length of each packet that gets sent, by setting the `length` attribute accordingly.

Exercise 9.2. *Lookup the source code of the* `ccc_send` *in the BTnut sources. How is sending data implemented? Why is* `ccc_send` *not doing the actual data transmission? Lookup the corresponding* `*_send` *function in* `bmac.c` *and explain.*

Explanation *Addressing in B-MAC*:
For each packet sent using `ccc_send`, a *destination address* must be given. The B-MAC implementation uses a two-tiered 16-bit address structure, composed of 2^{11} (i.e., 2048) *clusters* with $2^5 - 1$ (i.e., 31) individual addresses each. A reserved *broadcast address*, `BROADCAST_ADDR` (`0xFFFF`), can be used to address all nodes in all clusters. Each cluster (except for cluster 2047) also has a *multicast* address, which is simply the "highest" address in the cluster. Table 9.1 gives an overview.
In practice, the cluster address of a particular node does not matter much: As long as nodes are in range of each other, nodes from any cluster can send and receive data from nodes from any other cluster. Clusters are simply a means to form subgroups of nodes that can easily communicate among each other using a cluster-specific broadcast (called a "cluster-multicast"). Special care must be taken with such multicast addresses (i.e., addresses that are multiple of 32 minus one: 31, 63, 95, . . .), as data sent to such an address will be received by all other nodes in this particular cluster. When accidentially assigning such an address to a node (e.g., using `bmac_init(63)`), all packets sent to it will also be delivered (by the B-MAC layer) to all other nodes in this particular cluster (e.g., 32 through 62 in this case). Also note that cluster 2047 does not have an individual multicast address, as `0xFFFF` is actually used as a broadcast address for *all* nodes.
In order not to accidentially assign multicast addresses to nodes, use the following macro to compose an address from separate node and cluster IDs:

```
#define address (node, cluster) (((cluster) << 5) | (node))
```

When using `ccc_send`, we will need to take care of properly packaging our data. In case of binary data, this means making sure that multi-byte data (e.g., 16-bit shorts) are put in a well-defined order, otherwise the receiver might accidentially reverse those bytes during decoding. This is because not all microprocessors

Address	Node ID	Cluster ID
0x0000	0	0
0x001E	30	0
0x001F	*ALL*	0
0x0020	0	1
0x002E	30	1
0x002F	*ALL*	1
...	...	...
0xFFC0	0	2046
0xFFDE	30	2046
0xFFDF	*ALL*	2046
0xFFE0	0	2047
0xFFFE	30	2047
0xFFFF	*ALL*	*ALL*

Table 9.1: *Cluster Addresses.* The B-MAC layer divides the 16-bit address space into clusters with 31 nodes each. One address per cluster is reserved for so-called *cluster-multicast*, while the highest address (`0xFFFF`) broadcasts to all nodes in all clusters.

(nor compilers, for that matter) represent multi-byte values in the same order. Intel chips have traditionally arranged multi-byte values in memory by beginning with the *least significant byte* (LSB) first, i.e., the value `0x1234` stored at, say, memory address `0x3201`, would have the value `34` at `0x3201` and value `12` at `0x3202`. This is called "little-endian" order. Consequently, beginning with the *most significant byte* (MSB) first would store value `12` at `0x3201` and value `34` at `0x3202`. This is called "big-endian" order. This "endianness" becomes crucial when exchanging multi-byte data (e.g., integers) between platforms, e.g., through binary files (an image) or over the network.[5]

Explanation *Network Byte Order*:
As long as the data we send is picked up by identical hardware running identical software built using the same compiler, we can ignore byte order, as both sender and receiver will use the same representation. However, for exchanging data between different platforms, or between software from different generations, vendors, or compilers, agreeing on a common byte order is crucial. For network exchanges (e.g., over Ethernet, but also wirelessly), the commonly agreed upon *network byte order* uses big-endianness. There are standard C-functions, **`htons`** (*host-to-network-short*) and **`ntohs`** (*network-to-host-short*), to convert between this network byte order (where the most significant byte is put first) and the "host byte order", i.e., whatever the current host's and/or used compiler's order is.

```
void _cmd_send_ushort(char* arg) {
    int val;
    pkt->length = 2;

    if (sscanf(arg,"%u",&val)==1) {
        // put two-byte value (in network order) into packet
        *((u_short*) &pkt->data[0]) = htons((u_short) val);
        // /* alternatively, do this manually: */
        // pkt->data[0] = val>>8;   // high byte
        // pkt->data[1] = val&0xFF; // low byte
        if (ccc_send(BROADCAST_ADDR, PACKET_TYPE, pkt)) {
            /* send failed (<> 0 indicates error) */
        }
   }
}
```

[5]Notice that the concept of endianness is less important with regards to the individual *bits*, as access to bits is usually not given directly, but through well defined logical operators that work independant of the actual representation.

The second argument to `ccc_send` is a *packet types*. Packet types allow us to simplify packet receiption, as each different type can trigger a different reception function, so-called *packet handlers*. This is explained in the following section.

9.2.3 Receiving Data – The `ccc_rec` Receiver Thread

As we have seen in exercise 9.1 above, calling `ccc_init` automatically activates a `ccc_rec` thread that will repeatedly listen for incoming packets on the CC1000 radio. The `ccc_rec` thread is started with the relatively high priority of 16, in order to prevent delaying packet reception. This thread listens on a specific event handler for incoming data packets (as signaled by the B-MAC *low power listening* implementation), and in turn calls type-specific *packet handlers* for each received packet.

Packet handlers are registered using the `ccc_register_packet_handler` function and must implement the `void pkt_handler(ccc_packet_t *pkt)` interface. An example is shown below:

```
void pkt_handler(ccc_packet_t *pkt)
{
        u_short i;
    if (sscanf(pkt->data,"%u",&i) == 1) {
        printf ("Received Value: '%u'\n", i);
    } else { /* error parsing stringified data packet */ }
}

#define PACKET_TYPE  0x01

int main (void) {
    ...
    ccc_register_packet_handler(PACKET_TYPE, pkt_handler);
    ...
}
```

Explanation *B-MAC Packet Handlers*:
A packet handler is always assigned to a single packet type, and will thus only be called when the `ccc_rec` thread not only received a properly *addressed* packet, but also one with a matching *type*. These types are (currently) application specificy, i.e., you need to define the necessary type IDs (from 0–255) yourself. For example, an application might decide to define several such types in order to differentiate between status messages, sensory data, and routing information:

```
#define SENSOR_DATA  0x01
#define ECHO_REQUEST 0x04
#define ECHO_REPLY   0x05
#define ROUTING_TBL  0x09
```

Exercise 9.3. *Write a small chat program, consisting of a terminal command* `say`*, which simply sends off its arguments via broadcast, and a corresponding packet handler that listens for such packets and writes their source and contents to stdout in a chat-program fashion (e.g.,* `[45] says: Hello world`*).*

Optional Exercise 9.4. *Extend the program from ex. 9.3 to take an address for the* `say` *command (e.g.,* `say 345 hello world`*). Use* `say all` *or an additional* `shout` *command to initiate broadcasts.*

Exercise 9.5. *Write a program that periodically (e.g., every 2-4 seconds) sends out* `PING_TYPE` *packets to the broadcast address. A specific packet-handler for these packets should print out a brief message everytime it receives such a packet. Install your program on two BTnodes and observe them on two separate terminals.*

Explanation ***The B-MAC Packet struct*****:** A Chipcon packet is defined as shown below. It not only contains the actual packet payload, but also information about the packet's sender (`pkt->src`).

```
struct ccc_packet_t {
    /** source of the packet */
    u_short src;
    /** destination of the packet */
    u_short dst;
    /** payload length */
    u_short length;
    /** packet type */
    u_char type;
    /** payload data */
    u_char data[0];
}
```

Exercise 9.6. *Change your program from ex. 9.5 so that* `PING_TYPE` *packets are only sent out after no packet has been received for some time (use a timer). Upon reception of a* `PING_TYPE` *package, a* `PONG_TYPE` *package should be sent out, and vice versa (make sure that the timer is reset after a packet has been received). Print corresponding "ping" and "pong" messages upon sending each packet type. Watch the output of both nodes over two separate terminals, occasionally reseting one node to see whether your program works in both directions. Don't forget to reset the timer upon packet reception.*

Attention: CC1000 reception using *battery power* is extremely unreliable in the current BTnut release (1.8). This is most likely a software problem and should hopefully be fixed in future releases. Until then, we recommend using USB power when trying to receive data of the CC1000.[6]

9.3 Advanced Topics

Two interesting features of the CC1000 radio are that both its frequency and its power output can easily be adjusted, allowing for example frequency-hopping schemes or minimal-power transmissions.

9.3.1 Power Control

Transmission power can be set using the `cc1000_set_RF_power` function, which can be found in `cc1000.h`. It accepts a value from 0 to 255, with 0 being no power, 1 being the minimal power, and 255 representing maximum transmission power.

```
#include <cc/cc1000.h>

void rfpower_cmd(char *arg)
{
        u_short num;
        u_char num2;

    if (( sscanf(arg, "%u", &num) != 1 ) || num > 255 )
    {
        printf("usage: rfpower <0..255>\n");
        cc1000_get_RF_power( &num2 );
        printf( "Current RF power level is %u.\n", num2 );
        return;
    }
```

[6] *Sending* data, however, works fine both under battery and USB power.

```
    printf( "Setting RF power to %u...\n", num );
    cc1000_set_RF_power( num );
}
```

Exercise 9.7. *Write a program to measure the transmission distance for different power levels, i.e., find out how far away a signal sent with tranmission power 1, 2, or 3 can be still received, or how much power is necessary to contact a node at, say, 5 meter distance, or in another room.*

Optional Exercise 9.8. *Change your program from ex. 9.6 so that* `PING_TYPE` *packets include as payload the sender's current power level, initially set to its maximum of 255. Upon receiving such a packet, the receiver should print this information to STDOUT and acknowledge it with a* `PONG_TYPE` *packet. Receiving a* `PONG_TYPE` *packet should lower a sender's transmission power before sending out another* `PING_TYPE` *packet. Take two nodes and measure various distances that certain power levels can achieve.*

Optional Exercise 9.9. *Extend your program from ex. 9.7 so that it will build a neighborhood table of the closest n neighbors and their "power-level" distances.*

Optional Exercise 9.10. *Implement a multi-hop flooding protocol on the BTnodes. You will need to set the power level to a reasonably small number, e.g., 2-3. All packets will be sent to the broadcast address, and contain a packet ID that allows nodes to detect packets they already sent (in order to avoide reduplicating packets). Test your protocol by flooding your network with a certain LED pattern, i.e., use a terminal to initiate a certain LED pattern, which will be set on each receiving node (before sending the packet on to other nodes).*

9.3.2 Frequency Control

The CC1000 radio supports a wide variety of frequencies, primarily in the ISM-bands[7] at 315, 433, 868, and 915 MHz. However, it can be also tuned to almost any frequency between 300 and 1000 Mhz [4].

During B-MAC initialization, the radio is set to 868.5 MHz. However, if desired, one can use the `cc1000_set` function (in `cc1000.h`) to set it to one of 65 predefined frequencies in the 915 and 868 MHz bands, as defined in *cc1000_ defs.h*:

```
#include <cc/bmac.h>
#include <cc/ccc.h>
#include <cc/cc1000_defs.h>
#include <cc/cc1000.h>

#define address (node, cluster) (((cluster) << 5) | (node))
#define NODE_ADDRESS address (27, 34); /* node #27, cluster #34 */

static void init_radio (void) {
    bmac_init(NODE_ADDRESS);   /* inits radio to 868.5 MHz */
    cc1000_set(FREQ_915_430_MHZ); /* reset radio frequency (broken in release 1.6!!) */
    ccc_init(&bmac_interface);
}
```

Unfortunately, the `cc1000_set` function is broken in the BTnut 1.8 system release. This will hopefully be fixed soon.

The `cc1000_tune_manual` function offers even more control over the CC1000 frequency. The function takes the desired frequency in Hz (to avoid fractional values) and returns the actual frequency that has been set (as not all frequencies can be achieved on the CC1000).

```
uint32_t cc1000_tune_manual(uint32_t DesiredFreq);  /* interface */
```

[7]ISM stands for "Industrial, Scientific, Medial" and denotes frequency spectrums that can be used without acquiring a license first.

```
static void init_radio (uint32_t desiredFrq) {
    uint32_t actualFrq;
    bmac_init(NODE_ADDRESS);   /* inits radio to 868.5 MHz */
    actualFrq = cc1000_tune_manual(desiredFrq); /* reset radio frequency */
    printf ("[init_radio] set cc1000 to %lu Hz\n", actualFrq);
    ccc_init(&bmac_interface);
}
```

As this is still considered experimental, no header file is yet available. Simply include the interface as shown above. Also, the version contained in the 1.8 system release does not compile (due to redefinitions) – be sure to use an updated version either from CVS or from the tutorial homepage.

Exercise 9.11. *Manually set the frequency of one of your nodes to 868.5 Mhz, the B-MAC default frequency. Observe the actual frequency that the CC1000 gets tuned to (as returned by* `cc1000_tune_manual`*) and compare. Can you still receive packets sent from this node on a node that is not manually tuned? Explain why this works or does not work.*

Optional Exercise 9.12. *Extend your program from ex. 9.6 so that each packet also contains the frequency on which the next packet should be sent (use* `cc1000_set` *together with a number between 0 and 64 to choose from one of the 65 predefined frequencies). Take packet-loss into account, i.e., make sure that a lost packet will not put the two nodes permanently out of synch.*

9.3.3 Measuring Signal Strength

The CC1000 additionally offers access to RSSI (*Receive Signal Strength Indication*) information. However, as this data is available only in analog form, we will need to use on of the available ADCs (digital/analog converter) on the Atmega128 in order to obtain a digital readout. Access and usage of the ADCs is covered in the sensor chapter of this tutorial (see chapter 10). The many layers between our main program and the BTnut CC1000 modules further complicate matters: by the time one of our packet handlers gets called, packet reception has already finished, so reading out RSSI data at this point will most likely only measure the channel's background noise.[8]. Even if noise levels are all you want, measuring RSSI in your own program will most certainly interfere with B-MAC's CCA routines, requiring careful coordination of ADC registers in order not to mix up different RSSI readings.

Optional Exercise 9.13. *Where would we need to measure RSSI in order to obtain the signal strength with which a particular packet was received? Look trough the three modules* `ccc.c`*,* `bmac.c`*, and* `cc1000.c` *and speculate on the best place to add RSSI measurements to a data packet's struct.*

[8]B-MAC's *clear channel assignment* (CCA) feature actually requires measuring the current noise level on the channel, which is implemented by averaging a number of RSSI measurement. See the corresponding BTnut source code in `btnut/cc/cca.c`

Chapter 10

BTnodes and Sensors

While the BTnode has been designed for conducting research in *Wireless Sensor Networks* (WSNs), it does not carry any onboard sensors. This is in contrast to other WSN-platforms, such as the Tmote Sky, which (optionally) comes with three onboard sensors (temperature, light, and humidity). The reason for not including a fixed set of sensors lies in its added flexibility: depending on the particular application, BTnodes can be equipped with seperate “sensor-boards” that contain only the required set of sensors and which can be directly connected to one of the external connector sockets on the BTnode.

Working with sensors on the BTnode thus requires us to choose either a pre-made sensor board, or to connect our own set of sensors directly to one of the BTnode’s connectors. In this tutorial, we will use the BTsense sensor board, developed as part of the 2006 Wireless Sensor Network lecture at the ETH Zurich’s Inst. of Pervasive Computing. It has been specifically designed to contain both analog (light) and digital (temperature and motion) sensors, as well as an actuator (buzzer). It is connected through the BTnode’s “Debug Connector” (called J2) on the side, and is designed to be attached (e.g., with some plaster material) to the side of the BTnode. Figure 10.1 shows the top of the board. In particular, the BTsense board features the following sensor and actuators (rev 1.1):

1. Microchip TC74 digital (I^2C) temperature sensor [9]
2. Taos TSL252R analog light sensor [13]
3. Napion AMN1 digital (binary) motion sensor (passive IR) [15]
4. muRata 7BB-12-9 piezoelectric buzzer [10]

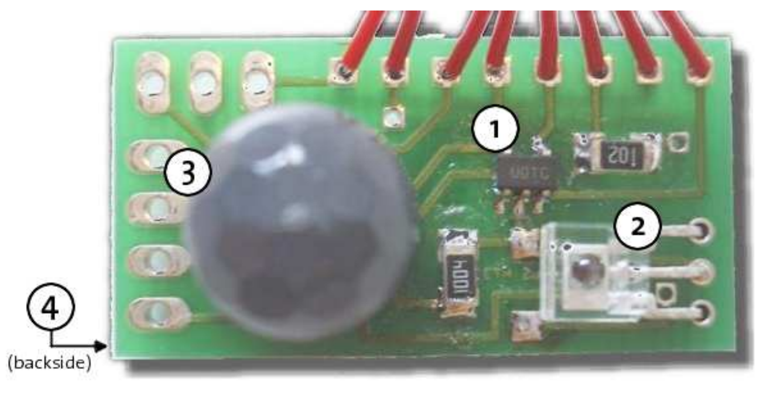


Figure 10.1: The BTsense rev1.1 sensor board.

Another popular alternative for connecting sensors to the BTnode is the set of boards developed at Teco in Karlsruhe. These boards have an extension connector that fits directly into the USB programming board. They come in several sizes and differ in the number of sensors they offer. The largest board, *spart*, additionally featured a separate microcontroller that would relieve the BTnode ATmega of any sensor related management tasks, though making its usage somewhat more difficult. The *ssmall* boards (without microcontroller) are available in a "medium" and "large" size and feature:

- Microchip TC74 digital (I^2C) temperature sensor
- Taos TSL2500 analog light sensor
- MAX8261 OP capacitive microphone
- ADXL210 2-axis acceleration sensor
- Second ADXL210 for combined 3-axis acceleration sensor (only on "full" version of the board)
- solder plates for optional pressure sensor, humidity sensor, second temp. sensor, speaker, etc.
- Two LEDs

In order to be able to gather sensor data on our BTnode, we first need to understand how its processor, the ATmega128L, receives and processes external data, and then how we can use BTnut to use this information in our program.

10.1 ATmega128L I/O-Ports and Registers

The ATmega128L microprocessor features 53 programmable I/O lines. It is through these lines that all communication to and from the processor takes place. While all 53 lines can be used in a totally generic fashion (i.e., they can both be used to output a bit, as well as reading input bits), all of them also have at least one so-called "alternate function", i.e., they are connected to a specific on-chip feature such as the analog-digital converter, the UART, a hardware timer, or an external interrupt signal. It is up to the programmer – either from within the OS, or as part of the application – to properly choose how a particular I/O line should be used: as a generic output line, as part of an ADC conversion, to monitor an input line and throw an interrupt whenever it changes, to control a set of digital sensors via a sensor-bus such as the I^2C-interface, etc.

Figure 10.2 shows all 64 pins of the ATmega128L. PA though PG are the seven available I/O ports, with ports A through F having 8 pins each, while port G has only five pins. Each port is represented through three registers each, which together provide – for each pin of each port – access to its I/O functionality: the *Data Direcion Register* (`DDRx`) (where x stands for A through G) defines whether a particular pin on a port will be used for input or output, while the *Data Register* (`PORTx`) and *Port Input Pin* (`PINx`) register (among other features) provide access to output and input values of each pin, respectively. Page 84 of the ATmega128L manual [1] gives an overview of all I/O port registers.

Additionally, more than one hundered registers can be used to enable or disable a certain "alternate function" of each pin. For example, the `ADCSRA` register controls the analog-digital converting unit – like turning it on and off, and starting a conversion – while the `ADMUX` register controls which of the potential input pins (pins 0 through 7 of port F) are to be used during the conversion.

Each of these registers (see the ATmega128L manual [1] on page 364 for a complete list) is provided to the programmer as a so-called *hardware register*. While programmers typically understand the term "register" to be a *processor register* – a small amount of very fast on-chip memory that is used to hold intermediate values during a computation in a very efficient manner – hardware registers are much more common in embedded systems programming. They often look and feel like being just another memory value, yet they physically control access to various devices. The avr-libc defines mnemonics[1] identical to the ones used in the ATmega128L manual as shorthands, in order to allow statements of the form "enable `ADEN` in the `ADCSRA` register" instead of "set bit 7 of register `0x0026` to 1".

[1]Actually: these are precompiler definitions, which can be found in `avr/io.h`.

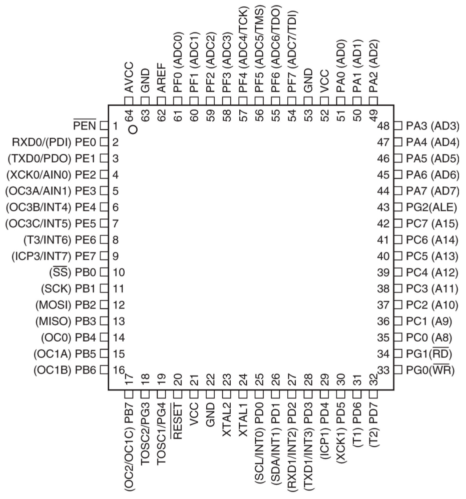


Figure 10.2: Ports of the ATmega128L [1].

Exercise 10.1. *Use the ATmega128L user manual [1] to find out which pins have the alternate function of serving as the data (SDA) and clock (SCL) line of the so-called "two-wire interface" (TWI). Find out what bit needs to be set in which hardware register in order to enable TWI support in the ATmega128L.*

Exercise 10.2. *Locate the schematic for the BTsense sensor board at www.btnode.ethz.ch (search under Hardware Reference) and find out to what ports and pins each of the three sensors – the light, temperature, and motion sensor – are connected.*

When using any kind of sensor platform with a BTnode, we thus first need to know how an individual sensor is connected to our microprocessor. Analog sensors will most certainly be connected (or have to be connected) to one of the ADC input pins, while digital ones either use TWI or are connected to a generic input pin. Knowing how and where a sensor is connected, we then need to understand the sensor's output, i.e. what information is delivered from the sensor to the input pin. This can be found in each sensor's *datasheet*. Last not least, we must then properly query these sensor values in our program: either by simply polling a sensor value repeatedly; using a timer to do this repeated polling for us; or by setting an interrupt to occur whenever a sensor value changes.

The following sections will describe each sensor type in turn, before outlining two possible ways of querying sensor values: polling and interrupts.

10.2 Sensor Types

BTnodes support three types of sensors: digital bus (I^2C) sensors, digital logic-level sensors, and analog sensors. Each type needs to be connected to different pins, each type needs a different way to read out a value. The sections below describe in detail how a generic sensor would need to be read out. However, for certain sensor platforms such as the BTsense sensor board, higher-level support is available in form of dedicated functions, alleviating the need for direct manipulations of the individual ATmega128L ports. Nevertheless, knowing the general principle of sensor read out should certainly foster overall understanding.

10.2.1 Digital I^2C-Bus Sensors

The I^2C-bus[2] was originally developed by Philips Semiconductors in the 1980s to simplify communication among various chips within TV-sets. It is a simple Master-Slave-bus, with a 7-bit address space that supports

[2]I^2C is pronounced "i-square-c", sometimes also "i-two-c".

up to 112 slave devices (16 addresses of the possible 128 are reserved).[3] The biggest advantage of the I^2C-protocol is its abilitiy to allow a single microcontroler the control of more than hundred devices with only two I/O-pins. The ATmega128L used in the BTnode supports the I^2C-protocol in hardware, which greatly simplifies control of I^2C-compatible devices. However, as I^2C is a registered trademark of Philips, Atmel calls this TWI ("two wire interface").

The two wires of the I^2C-bus are called SDA (data) and SCL (clock). Communication is always initiated by the master and is only between the master and a single slave. The clock is controlled by the master (this is handled by the ATmega128L for us) – it tells the slave when it should read a value from SDA (i.e., when SCL is high).[4] This allows the use of the I^2C-protocol also without fixed hardware or real-time clocks.

In order to poll an I^2C-sensor in BTnut, we need to know its address on the I^2C-bus. Addresses are defined in the corresponding header file (hopefully conflict-free) – in `btsense/btsense.h` for the BTsense board, and under `extras/teco_ssmall` for the *ssmall* board (both of which use the I^2C-compatible TC74 temperature sensor [9]).

Also, we need to know the corresponding I^2C-command that needs to be issued through the `TwMasterTransact`-function. This information can be found in the sensor's datasheet – for the TC74, the datasheet lists `0x00` as the command code for reading a temperature value.

Explanation *TWI-Communication in BTnut*:
NutOS comes with a simple two wire interface (TWI) library that works also on our ATmega128L. The most important commands are `TwInit` to initialize the interface, and `TwMasterTransact` to send commands to, and receive data from, the individual sensors.
`TwInit` takes a sole argument a 7-bit slave address, in order to allow (in theory) our master to also act as a slave to other masters on the bus. However, as the current implementation does not support slave mode for the ATmega128L, the parameter can safely be ignored (set it to 0, for example).
`TwMasterTransact` takes as a first argument the (slave) device address, followed by two variables each for sending and receiving data: (the address of) the variable where the command can be found, followed by its length, and the (address of the) variable where the received data should be put, followed by the maximum number of bytes to receieve. A final argument indicates a timeout value, which is currently not supported (will be ignored). It returns the number of bytes received, or -1 in case of error.

```
#include <dev/twif.h>

void main(void) {
    . . .
    // set TWI pins (Port D Pins 0 and 1) as Input w/ Pull-Up
    cbi(DDRD, DDD0); cbi(DDRD, DDD1); sbi(PORTD, PD0); sbi(PORTD, PD1);
    TwInit(0); // parameter currently ignored
    . . .
    u_char tw_cmd = 0x00; // "read temperature"-command
    u_char t;             // holds return value (temperature)

    if (TwMasterTransact(BTSENSE_I2C_TC74, &tw_cmd, 1, &t, 1, 0) == -1) {
       printf ("Error while reading sensor: %i\n", TwMasterError()); }
    . . .
}
```

The `TwInit` function simply initializes the software stack – it does not configure the corresponding ATmega128L ports for us. We therefor need to make sure that both of our TWI ports (i.e., pins 0 and 1 of Port D) are both configured for input (using the `DDRD` register) and have *pull-ups* enabled (using the `PORTD`).[5]

[3]The address space can optionally be extended to 10 bit and 1008 devices (1024-16), though this is not supported on the BTnode.

[4]During a high SCL level, SDA levels must be stable. Level changes on SDA during a high SCL indicate special START and STOP commands that a master uses to initiate or end a command.

[5]See page 65 of the ATmega128L user manual [1] for an overview of I/O-Port configuration.

Explanation *Pull-ups*:
Pull-ups are resistors in an electronic circuit that ensure that, given no other input, a circuit assumes a default value. The I^{2}C-protocol requires that when IDLE (i.e., when no devices use it), the bus remains in a logic HIGH state. This is achieved by inserting so-called *pull-up resistors* into the circuitry, which have the effect that as soon as at least one device puts a LOW value onto the bus, the whole circuit will be pulled to a logic LOW state. This allows other devices to detect communication on the bus.
Each of the 53 I/O-pins of the ATmega128L can have pull-ups enabled or disabled, using the `PORTx` register.

Also notice that the `TwMasterTransact` function references both the command variable *and* the result variable, i.e., it is not just for sending a command to a TWI-compliant device, but also for receiving its result.

Exercise 10.3. *Locate the TC74 datasheet off the BTsense documentation page on the BTnode Web site and find all supported I^{2}C-commands (with their corresponding command codes).*

10.2.2 Digital Logic-Level Sensors

Another type of digital sensor is that of the *logic-level* sensor. While also digital, it simply responds in a binary fashion: logical 1 and 0 (`VCC` and `GND`) represent "on" or "off", "detected" or "not detected", "critical" or "not critical". Such sensors do not need (and do not support) special communication protocols such as I^{2}C. Instead, we can directly connect them to one of the available I/O pins of the ATmega128L, configure the corresponding port-pin as "input" (using the `DDRx` register, cf. section 10.1) and read its value from the `PINx` register.

Explanation *Reading logic-level data in BTnut*:
Knowing to which pin a particular binary input is connected, we can easily define this pin as an input pin and read out its value. BTnut offers the *setbit* and *clearbit* functions – `sbi` and `cbi` – that set and clear individual bits of a selected register, respectively.
BTnut contains macros for all ATmega128L ports and pins, allowing for a convenient way of setting or clearing individual bits in a register. These macros are identical to the identifiers given in the ATmega128L reference manual [1] – see page 364 for an overview of all registers and pins.

```
// define pin 5 of port B as an input pin in port B's DDR register
cbi (DDRB, DDB5); // '0' means input pin
. . .
// read out all 8 pins of port B
u_char current_value_port_b = PORTB;
if (PORTB & (1<<PB5)) {
    // pin 5 is set
}
```

In many situations, it is important not simply to know a logic-level sensor's current value, but instead to know *when* it changes. The ATmega128L offers various *interrupts* that can be configured to observe an input pin for change, and trigger a program interruption whenever the output of such a logic-level sensor changes. More about such interrupts can be found in section 10.3.2 below.

Exercise 10.4. *Write a program that continously reads out (and prints) the value from the BTsense (logic-level) motion sensor. If you do not know to which port it is connected, see ex. 10.2 above.*

10.2.3 Analog Sensors

Analog sensors do not simply deliver an "off"/"on" value, but output a different voltage level for each possible sensor reading. In order to use this information in a program, this voltage level needs to be *sampled* into a binary value, typically between 0-255 (i.e., 8 bit resolution), though up to 10 bits resolution are supported on the ATmega128L.

Digitizing analog data on the ATmega128L is generally simple: its built-in Analog-Digital Converter (ADC) supports up to 8 different analog input channels (two of which optionally amplify the signal 10 or even 200 times), noise cancellation, and either single or continuous conversion modes. One only needs to properly setup the various needed parameters, trigger a conversion, and subsequently read out the resulting digital values. Each of these steps can be controlled through one or more ATmega128L registers.

Explanation *Using the ATmega128L ADC*:
ADC setup is performed through the *ADC Control and Status Register* (`ADCSRA`), where for example the ADC can be enabled and disabled (bit 7, `ADEN`), and single conversions can be triggered (bit 6, `ADSC`). The *ADC Multiplexer Selection Register* (`ADMUX`) allows the selection of input pins, as well as voltage reference and input gain setup. Note that before configuring the ADC, it should be turned off (i.e., the `ADEN` bit in `ADCSRA` should be cleared).
After starting a single conversion, the result is written to two registers, `ADCL` and `ADCH`. In order to know when the conversion is finished and these values can be read, one can simply check the value of the `ADSC` bit in the `ADCSRA` register: as soon as it is cleared, the result of the single conversion can be read. Alternatively, one can setup an ISR for the ADC interrupt (`sig_ADC`, see table 10.2 below) or wait for its corresponding flag (`ADIF` in the `ADCSRA` register) to be set. The default setup will put the LSB into `ADCL` and bits 8 and 9 into `ADCH`.

```
cbi(ADCSRA, ADEN); // disable ADC
ADCSRA = 0; // stop ADC & conv., no free-runn, no irq, def. prescaler
ADMUX  = 0; // AREF, ADLAR cleared, ADC0 input
sbi(ADCSRA, ADEN); // enable ADC
sbi(ADCSRA, ADSC); // start single conversion
// wait until conversion is finished
while (bit_is_set(ADCSRA, ADSC));
// find result in ADCL and ADCH
NutEnterCritical();
result = ADCL | (ADCH << 8);
NutExitCritical();
```

Note that its is important that reading out the final value is not temporarily suspended by a system interrupt (see more on interrupts in section 10.3.2 below), otherwise we might get a skewed result.

Exercise 10.5. *Use the above skeleton-code to write a program reading out the BTsense board's light sensor (if you do not know to which port it is connected, see ex. 10.2 above).*

In BTnut, the above ADC functions are encapsulated in the `dev/adc.h` library. All of the above mentioned functions – disabling, enabling, and configuring the ADC, as well as reading out converted values – can be achieved with a set of dedicated functions and corresponding constants, thus increasing code legibility and portability. However, the `adc.h` library is unable to cope with concurrent use, making it practically unusable. This is because other threads might concurrently use the ADC for other purposes (e.g., to measure the current battery level), thus reconfiguring the ADC repeatedly. In order to get reliable measurements, it is imperative to assert that the current ADC configuration still matches the desired one, or change it if otherwise. The `dev/adc2.h`-library offers the `adc2_init` and `adc2_read` functions, which are much more robust than their `dev/adc.h` counterparts and also support configuration validation.

Explanation *Using ADC in BTnut*:
The functions `adc2_init` and `adc2_read` are defined in the library `dev/adc2.h`. In contrast to the regular `dev/adc.h`-library, these functions also support ADC context switches, i.e., the concurrent use of the ADC by other threads.

```
#include <dev/adc2.h>

static u_short my_adc_handle;  // saves ADC context
int main (void) {
    my_adc_handle = adc2_init(ADC2_MODE_SINGLE_CONVERSION, ADC2_PRESCALE_DIV2,
                              ADC2_CHANNEL0, ADC2_REF_AREF);

    for (;;) {
        val = adc2_read(my_adc_handle); // read from prev. saved context
        printf("%d\n",val);
        NutSleep(1000);
    }
}
```

Optional Exercise 10.6. *Reimplement ex. 10.5 using the* `adc2.h` *library referenced above. How does the library support ADC-context switches? Locate the source code of* `adc2.c` *and look up.*

10.3 Reading Sensor Data

Depending on the type of sensor that we want to read out, different reading strategies might be appropriate.

10.3.1 Polling

Polling is the simplest yet least efficient way of reading sensor values. The simplest way would be to wrap the reading in a loop, potentially in a separate thread in order to allow the main program to continue executing other tasks. However, this approach ties up a lot of processing power and uses up precious energy when running under battery power. In most cases, one would want to at least include a `NutSleep` statement within the loop, to ensure that sensor readings only happen seconds or minutes apart (not milliseconds), e.g., for recording light or temperature values across several hours.

Instead of looping and repeatedly calling `NutSleep`, we can also let BTnut do the work for us, by using the `NutTimerStart` function described in section 4.4 above. By utilizing BTnut timers, repeated requests for sensor data can be scheduled over the course of hours, days, or even weeks. Given the 32-bit resolution of the `NutTimerStart` function, both one-shot and periodic timers of up to 49 days can be installed.

10.3.2 Interrupts

BTnut timers are a less resource intensive way of "manually" polling (e.g., in a loop) a sensor value. They are well suited for periodic measurement tasks, e.g., for documenting the temperature every 10 minutes over the course of a day. Sometimes, however, it is necessary to quickly react to a change in the measured data. Instead of increasing the polling frequency (and thus tying up CPU cycles), we can use an *interrupt* to get automatically notified of changing values.

The ATmega128L offers eight *external* interrupt request lines (i.e., pins that can automatically trigger the execution of a particular code snippet) and several *internal* interrupts (i.e., for monitoring internal processes, such as the above-mentioned counter overflows). Table 10.2 lists selected signals in BTnut – for a complete list of interrupts, see section *Interrupt Vectors* in the ATmega128L manual [1]. When interrupts are enabled, the processor will automatically interrupt the normal program flow and execute a previously registered *interrupt service routine* (ISR). As ATmega128L interrupts always have a higher priority than regular program code,

Mode	Description
NUT_IRQMODE_LOWLEVEL	Signal as long as level is low
NUT_IRQMODE_FALLINGEDGE	Signal when level changes to low
NUT_IRQMODE_RISINGEDGE	Signal when level changes to high
NUT_IRQMODE_EDGE	Signal whenever level changes

Table 10.1: BTnut external interrupt modes

they will be executed almost immediately when their interrupt condition holds true, allowing for almost real-time handling of events.

Explanation *Using interrupts in BTnut*:
In order to activate a particular interrupt in BTnut, we simply need to register an interrupt handler, a so-called *interrupt service routine*, with the corresponding *interrupt signal.* The `NutRegisterIrqHandler` function takes a signal, an ISR, and an optional argument to be passed to the ISR. Before assigning a new ISR, the interrupt in question should be turned off (using `NutIrqDisable`); *afterwards* it should of course be turned on (usign `NutIrqEnable`).
For external interrupts, which allow monitoring the logical level of up to eight input pins (`INT0` through `INT7`), we need to additionally clear its `DDRx` port bit (to define the pin as an input pin), and define for what kind of levels or level changes we want an interrupt. This is done with the *NutIrqSetMode* function, which takes an external interrupt signal and a trigger mode as input (again, this should be set *before* the input is enabled). Table 10.1 summarizes the various ways the pin level can be monitored.

```
#include <dev/irqreg.h>
. . .
void my_interrupt6_handler (void* arg) {
   static u_char my_variable = 0; // static variables for persistance
   . . .
}
. . .
NutIrqDisable( &sig_INTERRUPT6 );
cbi(DDRE, DDE6); // define pin E6 as input
NutRegisterIrqHandler(&sig_INTERRUPT6, my_interrupt6_handler, NULL);
NutIrqSetMode( &sig_INTERRUPT6, NUT_IRQMODE_EDGE );
NutIrqEnable( &sig_INTERRUPT6 );
```

What happens if an interrupt occurs during such an ISR? BTnut does not support stacked interrupts, so the current ISR will first be finished. When the system exists an ISR and finds another interrupt waiting (i.e., its corresponding interrupt bit is set) it will continue with executing the ISR of the next interrupt. However, while the current ISR was still running, there might have actually been multiple identical interrupts – e.g. a certain value crossed a threshold not only once (and threw an interrupt), but twice, or more often. As there is only one flag to indicate whether an interrupt has fired, there is no way to know how many interrupts have been missed during the execution of the current ISR. It is therefor important to keep the code inside an ISR as short as possible, in order to minimize the chances of missing out on important other interrupts, e.g., incoming packets on the Chipcon or Bluetooth radio. Another factor that should not be underestimated is the time it takes the system to switch between the main program and an ISR – typically tens or hundreds of CPU cycles, in order to save the current system state and switch to an ISR (and again back to the main program).

This uninterruptability of ISRs is sometimes also needed within the main program. For example, certain 16-bit registers of the ATmega128L need to be written to in an *atomic* fashion, e.g., either both bytes get written or none. If an interrupt occurs in the middle of such an assignment, the already written first byte might not be the same anymore by the time program control returns to the main program. BTnut offers the `NutEnterCritical` and `NutExitCritical` functions (in `sys/atom.h`) to allow main program code to run uninterrupted. As with ISR code, these parts of code should be as short as possible, in order not to loose any interrupt signals. Note that `NutExitCritical` does not simply re-enable interrupts. Instead,

Signal	Description
sig_ADC	ADC conversion complete
sig_COMPARATOR	Analog comparator
sig_INTERRUPT0	External interrupt 0
sig_INTERRUPT1	External interrupt 1
sig_INTERRUPT2	External interrupt 2
sig_INTERRUPT3	External interrupt 3
sig_INTERRUPT4	External interrupt 4
sig_INTERRUPT5	External interrupt 5
sig_INTERRUPT6	External interrupt 6
sig_INTERRUPT7	External interrupt 7
sig_SPI	SPI interrupt entry
sig_INPUT_CAPTURE1	Timer 1 input capture
sig_INPUT_CAPTURE3	Timer 3 input capture
sig_OUTPUT_COMPARE0	Timer 0 output compare
sig_OUTPUT_COMPARE1A	Timer 1A output compare
sig_OUTPUT_COMPARE1B	Timer 1B output compare
sig_OUTPUT_COMPARE1C	Timer 1C output compare
sig_OUTPUT_COMPARE2	Timer 2 output compare
sig_OUTPUT_COMPARE3A	Timer 3A output compare
sig_OUTPUT_COMPARE3B	Timer 3B output compare
sig_OUTPUT_COMPARE3C	Timer 3C output compare
sig_OVERFLOW0	Timer 0 overflow
sig_OVERFLOW1	Timer 1 overflow
sig_OVERFLOW2	Timer 2 overflow
sig_OVERFLOW3	Timer 3 overflow
sig_UART0_RECV	UART0 receive complete
sig_UART1_RECV	UART1 receive complete
sig_UART0_TRANS	UART0 transmit complete
sig_UART1_TRANS	UART1 transmit complete
sig_UART0_DATA	UART0 data register empty
sig_UART1_DATA	UART1 data register empty

Table 10.2: Selected `BTnut` interrupt signals

`NutEnterCritical` saves the current interrupt state before disabling them, so that `NutExitCritical` can restore whatever state previously existed. If interrupts were disabled before calling `NutEnterCritical`, they still stay disabled even after calling `NutExitCritical`.

10.3.3 Hardware Timers and Actuators

While adequate for issuing periodic sensor readings, the use of `NutTimerStart` has two important drawbacks: it only has a resolution of milliseconds, and actual code execution is thread-based, i.e., it might be delayed (potentially indefinitely) due to higher priority threads or non-yielding threads. In order to use more real-time and fine-grained timers, the integrated hardware timers of the ATmega128L can be used directly. This becomes important when driving actuators, e.g., the buzzer of the BTsense sensor board, or controlling motors based on pulse-width modulation (PWM).

The ATmega128L processor features two 8-bit and two 16-bit timers (Timer0 and Timer2, and Timer1 and Timer3, respectively). These simply work as *counters*, i.e., they continuously count from 0 to 255 (or 65535) and begin again from 0 afterwards. Whenever the counter overflows (i.e., starts again at 0), an *overflow interrupt* can be triggered, which allows a program to periodically execute a certain command. While Timer0 is already in use in BTnut to drive its timer functions (e.g., `NutTimerStart`, but also `NutSleep`), the remaining timers are available for use in your BTnut program.

Using a number of processor registers, one can customize the behavior of these counters. For example, by writing to the `OCRx` register (x being 0, 1, 2, or 3), we can set the so-called TOP value, i.e., the value at which an interrupt should be triggered. One can also switch a timer to the so-called *Clear Timer on Compare* (CTC) mode, where it restarts counting at zero whenever the counter reaches the TOP value (otherwise it continues to the 8-bit or 16-bit maximum).[6] Counters run at most with the speed of the main CPU – which runs at about 7.37MHz in the case of the ATmega128L on the BTnode.[7] Using a so-called *prescaler*, the counter can be slowed by factors of 8, 64, 256, or 1024. This can be set in the *Timer/Counter Control Register* `TCCRxn` (with x being 0, 1, 2, or 3, and n being A, B, or C for the two 16-bit counters only).

Explanation *Using a hardware timer in BTnut*:
The ATmega128L hardware timer/counter must be accessed directly through the corresponding hardware registers. The four timer are started by setting their corresponding prescaler value to non-zero value (see above). Also, one needs to set the count at which an interrupt and/or a reset to 0 should be triggered, as well as indicate what counter mode should be used (normal, CTC, etc.).

```
#include <sys/atom.h>
. . .
u_char max = 128;

// set counter mode to CTC (see ATmega128L manual p.156) in
// Timer/Counter2 Control Register TCCR2
sbi (TCCR2, WGM21); cbi (TCCR2, WGM20);

// set prescaler to 1024 (slowest timer possible), see p.157
sbi (TCCR2, CS22); cbi (TCCR2, CS21); sbi (TCCR2, CS20);

// make sure interrupts are turned off
NutEnterCritical();
// register interrupt handler to be called for 8-bit counter0
NutRegisterIrqHandler(&sig_OUTPUT_COMPARE2, my_timer2_handler, NULL);
// set TOP value (i.e., when interrupt should be triggered)
OCR2 = max;
// reset current counter value to zero
TCNT2 = 0x00;  // no need to start anything - counter runs continuosly
// enable interrupts again
NutExitCritical();
```

Exercise 10.7. *What type of counter do you need to generate waveforms for the 7BB-12-9 buzzer of the BTsense sensor board? You will have to take into account not only the desired signal frequency, but also the speed of the processor and the possible values of the prescaler. Hint: The corresponding chapters in the ATmega128L manual [1] contain a formula for computing a timer/counter's frequency.*

When setting the `OCx` pins as output pins (using the corresponding port's `DDRx` register), one can easily connect a waveform output to a peripheral device, such as a buzzer or a motor.[8] The `OCx` pins can be used in three different modes: *CTC*, *Fast PWM*, and *Phase Correct PWM*. In the already mentioned CTC mode, the `OCx` pin can be set to simply alternate (toggle) between 0 and 1 whenever the TOP values is reached (see figure 10.3 below). In Fast PWM mode[9], the counter always counts from BOTTOM to MAX. The `OCx` pin is cleared whenever the TOP value is reached, and set when the counter begins again at BOTTOM. This ensures PWM-signals with constant periods (i.e., from BOTTOM to TOP) that have a pulse width of exactly TOP (see figure 10.4 below). Phase-correct PWM finally creates the high pulse of the PWM signal

[6] Further counter modes can be found in the corresponding chapter of the ATmega128L manual [1].

[7] The exact processor speed can be obtained by calling `u_long NutGetCpuClock(void)`.

[8] The two 8-bit counters 0 and 2 have only one such pin – `OC0` and `OC2`, respectively – while the 16-bit counters 1 and 3 feature three such pins: `OC1A`, `OC1B`, `OC1C` and `OC3A`, `OC3B`, `OC3C`.

[9] PWM stands for *Pulse Width Modulation*.

always in the center of the period, not at its beginning flank, by counting from BOTTOM to TOP and back again, and inverting the signal when reaching TOP (both upwards and downwards, see figure 10.5 below).

When using a timer to drive an actuator connected to one of these pins, this has the advantage of not needing a separate interrupt service routine to explicitly set a pin output to 1 or 0: the timer/counter's corresponding `OCx`/`OCxn` will automatically alternate between 0 and 1 whenever the counter reaches its TOP and/or BOTTOM value.

Explanation *Putting a Waveform onto an I/O pin in BTnut*:
By connecting a device to the output pin of a 8-bit or 16-bit counter, we can directly modulate a corresponding signal onto the pin. This only requires that we set the data direction register of this pin (i.e., to define it as an "output" pin):

```
u_short max = 57535; // example

// set counter mode to CTC (see ATmega128L manual p. 131) in
// Timer/Counter1 Control Register TCCR1A
cbi (TCCR1A, WGM03); sbi (TCCR1A, WGM02);
cbi (TCCR1A, WGM01); cbi (TCCR1A, WGM00);

// set up output pin OCR1A to be toggled by counter
cbi (TCCR1A, COM1A1); sbi (TCCR1A, COM1A0);

// start counter with prescaler to 8 (example), see manual p. 135
cbi (TCCR1A, CS12); sbi (TCCR1A, CS11); cbi (TCCR1A, CS10);

// make sure interrupts are turned off
NutEnterCritical();
// no need for interrupt handler! simply set TOP value
OCR1 = max;
// reset current counter value to zero
TCNT1 = 0x0000;
// enable interrupts again
NutExitCritical();

// enable pin output for OC1A == PB5
sbi (DDRB, PB5);
```

Exercise 10.8. *Describe the steps necessary to put a 440Hz signal onto an* `OCxn` *pin.*

Optional Exercise 10.9. *Describe the steps necessary to put the same 440Hz signal onto an arbitrary I/O pin of the ATmega128L (e.g., pin PB4). What is the difference to the solution in ex. 10.8?*

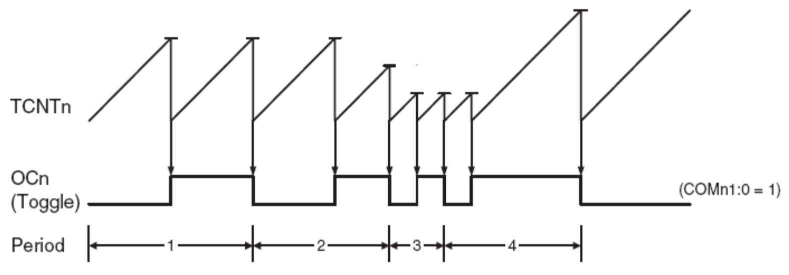


Figure 10.3: Waveform generation in CTC mode [1]. Notice the variable signal periods due to varying TOP values (horizontal bars).

10.4 The `btsense`-library

Many of the low-level details for querying sensor data off the BTsense sensor board have already been encapsulated in dedicated functions as part of the `btsense`-library. While it might still be necessary to use BTnut timers, interrupts, or hardware timers to read out sensor values periodically and/or automatically, these functions should greatly simplify the act of reading out each of the three sensors, as well as driving the connected buzzer.

Explanation *Using the library for BTsense*:
The `btsense`-library offers three functions for reading out each of the three sensors, as well as a function for driving the buzzer with a particular frequency. It takes care to properly set all required hardware registers, as well as configure both the ADC and any necessary timer/counters. Note that the `btsense_init` function requires a board revision identifier – typically this should be `BTSENSE_REVSION_1_1`.

```
#include <btsense/btsense.h>

int main(void) {
   btnode_init(); // init hardware, uart, network
   btsense_init( BTSENSE_REVISION_1_1 );

   u_short light = btsense_sample_light();
   printf ("Light Level: %d\n", light);
   u_char motion = btsense_sample_motion();
   printf ("Motion Level: %d\n", motion);
   u_char temp; int err;
   if (err = btsense_sample_temp(&temp)) {
      // TWI error
      printf ("TWI Error: %d\n", err);
   } else {
      printf ("Temperature Level: %d\n", temp);
   }
   // make a beep
   btsense_sound (440); NutSleep (1000); btsense_sound (0);

   for (;;) { NutSleep (5000) };
}
```

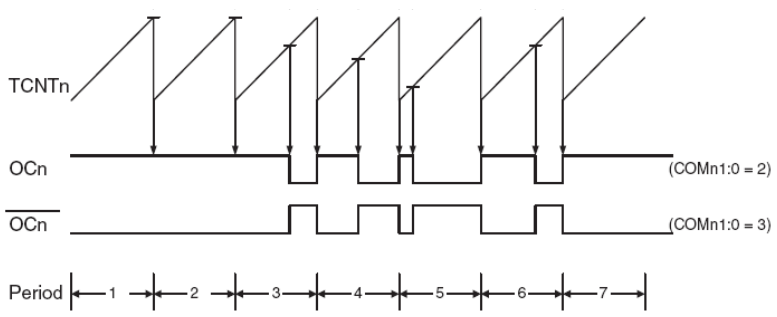


Figure 10.4: Waveform generation in Fast-PWM mode [1]. Periods are constant, signal width is according to TOP value (horizontal bars).

In addition to the `btsense`-library, a number of helper functions are available via `adc2/adc2.h` – see the source code for details.

Exercise 10.10. *Write a program that converts the light levels detected by the light sensor into a corresponding LED-meter, i.e., the brighter it is, the more LEDs light up.*

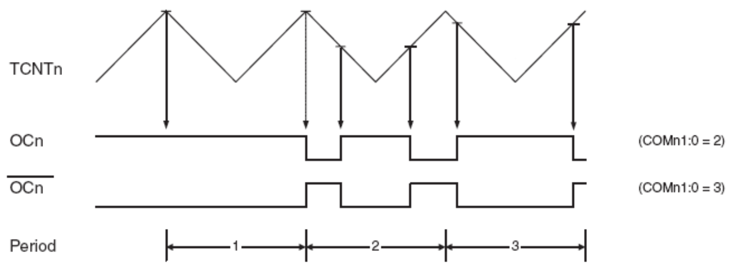


Figure 10.5: Waveform generation in Phase-Correct-PWM mode [1]. Notice how signals are centered within constant periods.

Optional Exercise 10.11. *Extend the program from ex. 10.10 to also sound the buzzer at different frequency levels, according to the detected light level.*

Exercise 10.12. *Write a program that indicates motion detection through LED or buzzer signaling. Instead of repeatedly polling the current value of the motion sensor, you should use set up an interrupt service routine to get triggered whenever the motion sensor's signal changes. Describe the output you observe.*

Exercise 10.13. *Extend the program from ex. 10.12 above to send motion events via the radio to a receiving node, which then prints out a corresponding line to the terminal.*

Optional Exercise 10.14. *Combine the motion sensors of several BTnodes in order to be able to detect the direction of motion, e.g., along a corridor or on both sides of a door. Both nodes should send motion events to a sink node, which then determines the direction of the motion and keeps an on-screen statistic (e.g., how many people entered and exited a certain room). Tip: In order to limit the area that the motion sensor covers, you can simply build a small paper cone and put it around the sensor.*

Optional Exercise 10.15. *Write a program that periodically reads out all available sensor values and sends them wirelessly to a sink node, which is connected to a laptop or PC via USB. Try to save power by grouping several measurements into a single transmission. The sink node should print out the comma-separated list of values to STDOUT, which can then be easily captured into a file by using the terminal's capture-to-file function and then displayed graphically in Excel, OpenOffice Spreadsheet, or GNUplot.*

Optional Exercise 10.16. *Extend the program from ex. 10.15 to work with multiple BTnodes, i.e., prefix each nodes measurements with a node ID. Try to minimize packet loss, e.g., by sending packets repeatedly. Use this setup to record one or two rooms over the course of an entire day. Prepare corresponding graphical plots.*

Appendix A

Software Versions Used

The BTnode tutorial is known to work with the following software versions:

`AVR Studio 4 v412SP1 build462`

`Silabs CP2101 USB to UART Bridge 20050102`

`WinAVR 20060125`

`doxygen 1.4.6`

`Java 2 SDK 1.5.0_06`

`RXTX-2.0-7pre1`

`javax_comm-2_0_3-solsparc`

`eclipse 3.1.2`

`org.eclipse.cdt.sdk-3.0.2`

`easyshell-1.2.0`

`ZOC Terminal 5.0.6`

`Emacs 21.2`

`Matlab 7.1r14`

Appendix B

Solutions

Solution 2.1 The external memory is connected to Port A (address and data bus) and Port C (address bus) as well as to three pins of Port G that are assigned WR*, RD* and ALE functions. A trandparent D-type latch is used to multiplex Port A in order to save IO space at the cost of longer access times. The BTnode rev3 further uses two pins of Port B (PB7 and PB6) to bank switch 4 banks of 60 kbytes external memory (the processor can only make use of one bank at a time).

The LED/power latch is attached to Port C. This allows to multiplex the address bus and the latch used for the LEDs and power/radio configuration onto Port C. It is controlled via pin PB5 (LATCH_SELECT).

Pin	**Function**
PC0	Blue LED
PC1	Red LED
PC2	Yellow LED
PC3	Green LED
PC4	ON_VCC_IO
PC5	ON_VCC_CC
PC6	ON_VCC_BT
PC7	RESET_BT

The first problem from this hardware setup is that the software has to keep track of the states of the latch outputs since it is impossible to inquire the current latch state at the port outputs in software. The second problem is that the routine for driving the latch should not be interruptible yet it has to be short so that it does not interfere too much with other software components timing requirements.

Solution 2.2 Project setup in Eclipse follows the menu functions and is straightforward.

Solution 2.3 The indexing function is a very powerful tool within Eclipse. It is much faster than global search and can discriminate definitions, declarations and references.

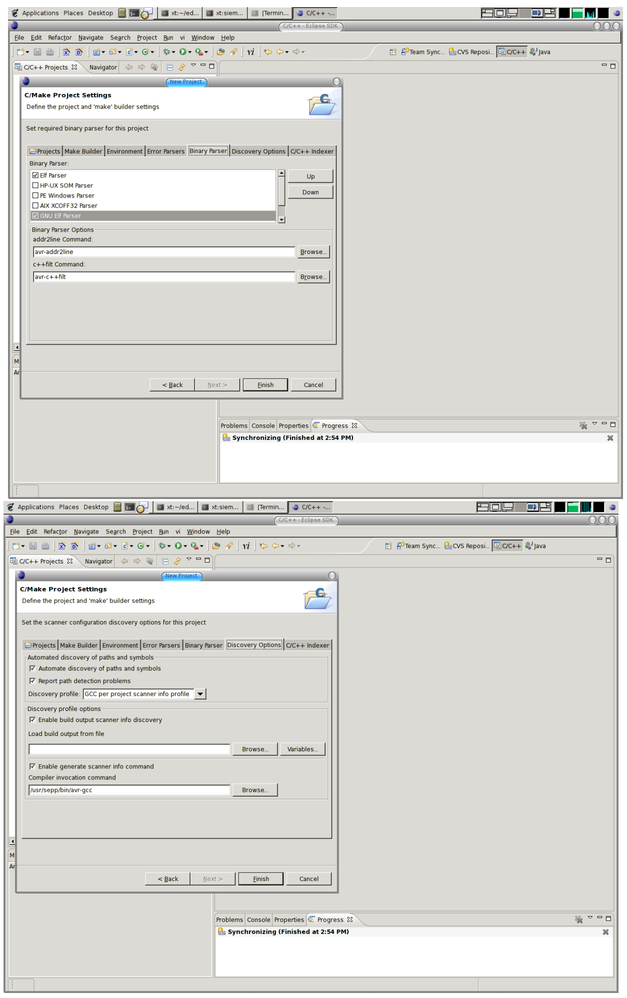
Solution 2.4 The BTnut system software supports scheduling of different patterns at the LEDs, a simple, yet powerful user interface on embedded systems.

Solution 2.5 The `Content Assist` function is yet another powerful feature when using Eclipse. It allows to quickly navigate different library functions and gives quick hints to their correct usage/syntax. Use it to add an additional LED pattern to a simple BTnut application:

```
btn_hardware_init();

btn_led_init(1);

btn_led_add_pattern(BTN_LED_PATTERN_HALF,0,10,BTN_LED_INFINITE);
```


Applications Places Desktop
C/C++ - Eclipse SDK
File Edit Refactor Navigate Search Project Run vi Window Help
C/C++ Projects
Navigator
New Project
Problems Console Properties Progress

C/Make Project Settings

Define the project and 'make' builder settings

Set required binary parser for this project

Projects | Make Builder | Environment | Error Parsers | Binary Parser | Discovery Options | C/C++ Indexer

Binary Parser:

- ☑ Elf Parser
- ☐ HP-UX SOM Parser
- ☐ PE Windows Parser
- ☐ AIX XCOFF32 Parser
- ☑ GNU Elf Parser

Binary Parser Options

addr2line Command: avr-addr2line

c++filt Command: avr-c++filt

Synchronizing (Finished at 2:54 PM)

C/Make Project Settings

Define the project and 'make' builder settings

Set the scanner configuration discovery options for this project

Projects | Make Builder | Environment | Error Parsers | Binary Parser | Discovery Options | C/C++ Indexer

Automated discovery of paths and symbols

- ☑ Automate discovery of paths and symbols
- ☑ Report path detection problems

Discovery profile: GCC per project scanner info profile

Discovery profile options

- ☑ Enable build output scanner info discovery

Load build output from file

- ☑ Enable generate scanner info command

Compiler invocation command: /usr/sepp/bin/avr-gcc

Synchronizing (Finished at 2:54 PM)

Figure B.1: Use the Eclipse menues to navigate the the new projects wizard.

Solution 2.6 The Atmel AVR is a family of simple yet very versatile microcontrollers based on an 8-bit RISC core running single cycle instructions. AVR instructions are tuned to decrease the size of the program whether the code is written in C or Assembly.

The AVR Libc implements simple fixed point arithmetic functions using commands from the AVR instruction set such as: `lds`, `xor` or `fmul`.

Due to it's simple core architecture mathematical operations requiring complicated processor hardware such as multiply and divide are omitted. However there are specialized libraries available that implement sets of mathematical functions (fixed point anf floating point) or even cryptography on the AVR architecture.

Some examples with online resources are:

- mikroPascal for AVR
- mikroBasic for AVR
- Procyon AVRlib

Solution 2.10

```
C:\Documents and Settings\es2005>avr-as --version
GNU assembler version 2.15 (avr) using BFD version 2.15 + coff-avr-patch (20030831)

C:\Documents and Settings\es2005>avr-gcc -v
Reading specs from C:/WinAVR/bin/../lib/gcc/avr/3.4.3/specs
Configured with: ../gcc-3.4.3/configure --prefix=m:/WinAVR --build=mingw32
--host=mingw32 --target=avr --enable-langu
Thread model: single
gcc version 3.4.3

C:\Documents and Settings\es2005>avr-ld -v
GNU ld version 2.15 + coff-avr-patch (20030831)

C:\Documents and Settings\es2005>uisp --version
uisp version 20050207
(C) 1997-1999 Uros Platise, 2000-2003 Marek Michalkiewicz
uisp is free software, covered by the GNU General Public License.
You are welcome to change it and/or distribute copies of it under
the conditions of the GNU General Public License.

C:\Documents and Settings\es2005>avrdude -v
avrdude: Version 4.4.0cvs
         Copyright (c) 2000-2004 Brian Dean, http://www.bdmicro.com/
         System wide configuration file is "C:\WinAVR\bin\avrdude.conf"
avrdude: no programmer has been specified on the command line or the config file
         Specify a programmer using the -c option and try again
```

Solution 2.11

```
avrdude -help
Usage: avrdude [options]
Options:
  -p <partno>                Required. Specify AVR device.
  -b <baudrate>              Override RS-232 baud rate.
  -B <bitclock>              Specify JTAG/STK500v2 bit clock period (us).
  -C <config-file>           Specify location of configuration file.
  -c <programmer>            Specify programmer type.
  -D                         Disable auto erase for flash memory
  -P <port>                  Specify connection port.
  -F                         Override invalid signature check.
  -e                         Perform a chip erase.
  -U <memtype>:r|w|v:<filename>[:format]
                             Memory operation specification.
                             Multiple -U options are allowed, each request
                             is performed in the order specified.
  -n                         Do not write anything to the device.
  -V                         Do not verify.
  -u                         Disable safemode, default when running from a script.
  -s                         Silent safemode operation, will not ask you if
                             fuses should be changed back.
  -t                         Enter terminal mode.
  -E <exitspec>[,<exitspec>] List programmer exit specifications.
  -y                         Count # erase cycles in EEPROM.
  -Y <number>                Initialize erase cycle # in EEPROM.
  -v                         Verbose output. -v -v for more.
  -q                         Quell progress output. -q -q for less.
  -?                         Display this usage.

avrdude project: <URL:http://savannah.nongnu.org/projects/avrdude>
```

Solution 2.12

```
avrdude: AVR device initialized and ready to accept instructions
Reading | ################################################## | 100% 0.02s
avrdude: Device signature = 0x1e9702
avrdude: safemode: Fuses OK
avrdude done.  Thank you.
```

Solution 2.13

```
avrdude: AVR device initialized and ready to accept instructions
Reading | ################################################## | 100% 0.02s
avrdude: Device signature = 0x1e9702
avrdude: reading input file "bt-cmd.btnode3.hex"
avrdude: writing flash (66182 bytes):
```

```
Writing | ################################################## | 100% 14.47s
avrdude: 66182 bytes of flash written
avrdude: safemode: Fuses OK
avrdude done.  Thank you.
```

Solution 2.15

```
avrdude: AVR device initialized and ready to accept instructions
Reading | ################################################## | 100% 0.02s
avrdude: Device signature = 0x1e9702
avrdude: NOTE: FLASH memory has been specified, an erase cycle will be performed
         To disable this feature, specify the -D option.
avrdude: erasing chip
avrdude: reading input file "uart-echo.btnode3.hex"
avrdude: writing flash (13410 bytes):
Writing | ################################################## | 100% 2.95s
avrdude: 13410 bytes of flash written
avrdude: verifying flash memory against uart-echo.btnode3.hex:
avrdude: load data flash data from input file uart-echo.btnode3.hex:
avrdude: input file uart-echo.btnode3.hex contains 13410 bytes
avrdude: reading on-chip flash data:
Reading | ################################################## | 100% 1.48s
avrdude: verifying ...
avrdude: 13410 bytes of flash verified
avrdude: safemode: Fuses OK
avrdude done.  Thank you.
```

Solution 2.16

```
make btnode3
echo "#define PROGRAM_VERSION "\""20060405-1501"\" > program_version.tmp
mv -f program_version.tmp program_version.h
avr-gcc -c -mmcu=atmega128 -Os -Wall -Werror -Wstrict-prototypes -Wa,-ahlms=bt-cmd.btnode3.lst -D__HARVARD_ARCH__
-D__BTNODE3__ -DUSE_USART0 -DUART0_READMULTIBYTE -DUART0_NO_SW_FLOWCONTROL -DUSE_USART1 -DUART1_READMULTIBYTE
-DUART1_NO_SW_FLOWCONTROL -I../..//btnode/include -I../..//../nut/include bt-cmd.c -o bt-cmd.btnode3.o
avr-gcc bt-cmd.btnode3.o  ../..//lib/btnode3/nutinit.o -Wl,--start-group -L../..//lib/btnode3 -mmcu=atmega128
-Wl,--defsym=main=0,-Map=bt-cmd.btnode3.map,--cref -L../..//lib/btnode3 -lnutos -lnutdev -lnutarch -lnutcrt
-lbt -lhardware -lcm -leepromdb -lsuart -lled -lcc -ldebug -lmhop -lsync -lutils -lterminal -lsupport -lcdist
-Wl,--end-group -o bt-cmd.btnode3.elf
avr-size bt-cmd.btnode3.elf
   text    data     bss     dec     hex filename
  60416    4062    2814   67292   106dc bt-cmd.btnode3.elf
avr-objcopy -O ihex bt-cmd.btnode3.elf bt-cmd.btnode3.hex
rm bt-cmd.btnode3.elf

make btnode3 upload
make: Nothing to be done for ‘btnode3’.
make burn.btnode3
make[1]: Entering directory ‘/home/beutel/eclipse/btnut/app/bt-cmd’
avrdude -pm128 -cavrispv2 -Pusb -s     -U flash:w:bt-cmd.btnode3.hex:i

avrdude: AVR device initialized and ready to accept instructions

Reading | ################################################## | 100% 0.01s

avrdude: Device signature = 0x1e9702
avrdude: NOTE: FLASH memory has been specified, an erase cycle will be performed
         To disable this feature, specify the -D option.
avrdude: erasing chip
avrdude: reading input file "bt-cmd.btnode3.hex"
avrdude: writing flash (64478 bytes):

Writing | ################################################## | 100% 5.19s

avrdude: 64478 bytes of flash written
avrdude: verifying flash memory against bt-cmd.btnode3.hex:
avrdude: load data flash data from input file bt-cmd.btnode3.hex:
avrdude: input file bt-cmd.btnode3.hex contains 64478 bytes
avrdude: reading on-chip flash data:

Reading | ################################################## | 100% 4.17s

avrdude: verifying ...
avrdude: 64478 bytes of flash verified

avrdude: safemode: Fuses OK
```

```
avrdude done.  Thank you.

make[1]: Leaving directory ‘/home/beutel/eclipse/btnut/app/bt-cmd’
```

Solution 3.1 The blue LED is connected to pin 0 of port C. Since port C is the upper byte of the address bus, the value `0x0100` on the address bus switches on the blue LED. Since the function `write_led` shifts the argument value by 8 bits, you have to use `write_led(0x01)` to switch on the blue LED.

Solution 3.2

```
#include <hardware/btn-hardware.h>  // btn_hardware_init

void shortpause(u_short duration)
{
    u_short i;
    for (i=0;i<duration;i++) {
    }
}

void pause(u_short duration)
{
    u_short i;
    for (i=0;i<duration;i++) {
        shortpause(0xffff);
    }
}

void write_led(u_char value)
{
    volatile u_char * pointer;
    u_char dummy;

    pointer  = (u_char *) ( ((u_short)value) << 8);
    dummy    = *pointer;

    sbi(PORTB, 5);
    asm volatile  ("nop" ::);
    cbi(PORTB, 5);
}

int main(void)
{
    int toggle = 0;

    sbi(DDRB, 5);
    while (1) {
        if (toggle) {
            toggle = 0;
            write_led(0x01);
        }
        else {
            toggle = 1;
            write_led(0x00);
        }
        pause(12);
    }
    return 0;
}
```

Solution 3.3 I have implemented the pause with the help of a `shortpause()` function. Calling `pause(12)` resulted in a pause of approximately 1 second. Calling `pause(12)` runs the loop in `shortpause` $12 \cdot$`0xffff` $= 768'000$ times. Now we look at the list file:

```
  ...
  13                        shortpause:
  14                        /* prologue: frame size=0 */
  15                        /* prologue end (size=0) */
  16 0000 20E0                      ldi r18,lo8(0)
  17 0002 30E0                      ldi r19,hi8(0)
  18 0004 2817                      cp r18,r24
  19 0006 3907                      cpc r19,r25
  20 0008 28F4                      brsh .L8
  21                        .L6:
  22 000a 2F5F                      subi r18,lo8(-(1))
```

```
 23 000c 3F4F                   sbci r19,hi8(-(1))
 24 000e 2817                   cp r18,r24
 25 0010 3907                   cpc r19,r25
 26 0012 D8F3                   brlo .L6
 27                     .L8:
 28 0014 0895                   ret
 29                     /* epilogue: frame size=0 */
 30                     /* epilogue: noreturn */
 31                     /* epilogue end (size=0) */
 32                     /* function shortpause size 11 (11) */
 33                            .size        shortpause, .-shortpause
 ...
```

The loop is coded in the lines 21 to 26, line 21 is not an instruction, thus the loop is 5 instructions long. So in 1 second, approximately $768'000 \cdot 5 = 3'930'000$ instructions are executed. Assuming that every instruction takes one cycle results in a clock frequency of 3.9 MHz.

Looking at the instruction set summary in the atmega manual tells us that the |`brlo`|takes two cycles, thus we get to a clock frequency of $768'000 \cdot 6\ Hz = 4.7MHz$.

The clock frequency is actually 7.3 MHz. The error of course results from the extremely inaccurate measurement of 'one second'.

Solution 3.4

```
#include <hardware/btn-hardware.h>

// COMPUTE ADC values corresponding to 1 and 2 Volts:
// If battery voltage is 1V, the BAT_SENSE signal is 0.5V.
// The reference voltage is 3.3V and corresponds to the ADC value 1024.
// Therefore 0.5V corresponds to an ADC value of 1024/3.3*0.5=155.
// A battery voltage is 2V, ADC value is 310.
#define BAT_1_VOLT 155
#define BAT_2_VOLT 310

void shortpause(u_short duration)
{
    u_short i;
    for (i=0;i<duration;i++) {
    }
}

void pause(u_short duration)
{
    u_short i;
    for (i=0;i<duration;i++) {
        shortpause(0xffff);
    }
}

void write_led(u_char value)
{
    volatile u_char * pointer;
    u_char dummy;

    pointer  = (u_char *) ( ((u_short)value) << 8);
    dummy    = *pointer;

    sbi(PORTB, 5);
    asm volatile  ("nop" ::);
    cbi(PORTB, 5);
}

int get_battery_voltage(void) {

    int result;

    ADMUX |= 1<<MUX0;
    ADMUX |= 1<<MUX1;
    ADCSRA |= 1<<ADPS0;
    ADCSRA |= 1<<ADPS1;
    ADCSRA |= 1<<ADPS2;
    ADCSRA |= 1<<ADEN;
    ADCSRA |= 1<<ADSC;
    while (ADCSRA & (1<<ADSC)) ;

    result = ADCL;
    result |= ADCH << 8;

    return result;
}

int main(void)
{
    int battery_voltage = 0;

    DDRB |= 1<<DDB5;
    while (1) {

        battery_voltage = get_battery_voltage();

        if (battery_voltage < BAT_1_VOLT) {
           write_led(0x02);
        }
        else {
            if (battery_voltage < BAT_2_VOLT) {
               write_led(0x04);
            }
            else {
               write_led(0x08);
            }
        }
        pause(12);
        write_led(0x01);
        pause(12);
    }
    return 0;
}
```

Solution 3.5

```
#include <hardware/btn-hardware.h>
#include <dev/irqreg.h>

// COMPUTE ADC values corresponding to 1 and 2 Volts:
// If battery voltage is 1V, the BAT_SENSE signal is 0.5V.
// The reference voltage is 3.3V and corresponds to the ADC value 1024.
// Therefore 0.5V corresponds to an ADC value of 1024/3.3*0.5=155.
// A battery voltage is 2V, ADC value is 310.
#define BAT_1_VOLT 155
#define BAT_2_VOLT 310

void shortpause(u_short duration)
{
    u_short i;
    for (i=0;i<duration;i++) {
    }
}

void pause(u_short duration)
{
    u_short i;
    for (i=0;i<duration;i++) {
        shortpause(0xffff);
    }
}

void write_led(u_char value)
{
    volatile u_char * pointer;
    u_char dummy;

    pointer  = (u_char *) ( ((u_short)value) << 8);
    dummy    = *pointer;

    sbi(PORTB, 5);
    asm volatile  ("nop" ::);
    cbi(PORTB, 5);
}

int get_battery_volt(void) {

    int result;

    ADMUX |= 1<<MUX0;
    ADMUX |= 1<<MUX1;
    ADCSRA |= 1<<ADPS0;
    ADCSRA |= 1<<ADPS1;
    ADCSRA |= 1<<ADPS2;
    ADCSRA |= 1<<ADEN;
    ADCSRA |= 1<<ADSC;
    while (ADCSRA & (1<<ADSC)) ;

    result = ADCL;
    result |= ADCH << 8;

    return result;
}

static void timer3IRQ(void *arg)
{
    int battery_voltage = get_battery_volt();

    if (battery_voltage < BAT_1_VOLT) {
       write_led(0x02);
    }
    else {
        if (battery_voltage < BAT_2_VOLT) {
           write_led(0x04);
        }
        else {
           write_led(0x08);
        }
    }
    // Reset the counter to non-zero value, see expl. in main routine.
    TCNT3H = 0x21;
    TCNT3L = 0x64;
}

int main(void)
{
    int toggle = 0;

    DDRB |= 1<<DDB5;

    NutRegisterIrqHandler(&sig_OVERFLOW3, timer3IRQ, 0);
    // 16 bit timer without prescaler (clock frequency 7.3MHz)
    // -> overflows once every 0xffff*(1/7.3E6)s=9ms
    // For an overflow every 2s, prescaler should be
    // 2s/9ms = 223. The closest value is 256 (see table on page 135).
    // This gives an overflow every 2.3s. This could be adjusted by
    // setting the counter value to 0.3/2.3*0xfffff = 0x2164 after
    // every overflow, thus at the end of the timer interrupt routine
    TCCR3B |= 1<<CS32;
    ETIMSK |= 1<<TOIE3;


    while (1) {
        if (toggle) {
            toggle = 0;
            write_led(0x01);
        }
        else {
            toggle = 1;
            write_led(0x00);
        }
        pause(10);
    }

    return 0;
}
```

Solution 3.6

```
#include <hardware/btn-hardware.h>
#include <dev/irqreg.h>

// COMPUTE ADC values corresponding to 1 and 2 Volts:
// If battery voltage is 1V, the BAT_SENSE signal is 0.5V.
// The reference voltage is 3.3V and corresponds to the ADC value 1024.
// Therefore 0.5V corresponds to an ADC value of 1024/3.3*0.5=155.
// A battery voltage is 2V, ADC value is 310.
#define BAT_1_VOLT 155
#define BAT_2_VOLT 310

void shortpause(u_short duration)
{
    u_short i;
    for (i=0;i<duration;i++) {
    }
}

void pause(u_short duration)
{
    u_short i;
    for (i=0;i<duration;i++) {
        shortpause(0xffff);
    }
}

void write_led(u_char value)
{
    volatile u_char * pointer;
    u_char dummy;

    pointer  = (u_char *) ( ((u_short)value) << 8);
    dummy    = *pointer;

    sbi(PORTB, 5);
    asm volatile  ("nop" ::);
    cbi(PORTB, 5);
}

int get_battery_volt(void) {

    int result;

    ADMUX |= 1<<MUX0;
    ADMUX |= 1<<MUX1;
    ADCSRA |= 1<<ADPS0;
    ADCSRA |= 1<<ADPS1;
    ADCSRA |= 1<<ADPS2;
    ADCSRA |= 1<<ADEN;
    ADCSRA |= 1<<ADSC;
    while (ADCSRA & (1<<ADSC)) ;

    result = ADCL;
    result |= ADCH << 8;

    return result;
}

static void timer3IRQ(void *arg)
{
    int battery_voltage = get_battery_volt();

    if (battery_voltage < BAT_1_VOLT) {
       write_led(0x02);
    }
    else {
        if (battery_voltage < BAT_2_VOLT) {
           write_led(0x04);
        }
        else {
           write_led(0x08);
        }
    }
}

int main(void)
{
    int toggle = 0;

    DDRB |= 1<<DDB5;

    NutRegisterIrqHandler(&sig_OUTPUT_COMPARE3A, timer3IRQ, 0);
    // 16 bit timer without prescaler (clock frequency 7.3MHz)
    // -> overflows once every 0xffff*(1/7.3E6)s=9ms
    // For an overflow every 2s, prescaler should be
    // 2s/9ms = 223. The closest value is 256 (see table on page 135).
    // This gives an overflow every 2.3s.
    TCCR3B |= 1<<CS32;
    // To get an interrupt every 2s, the interrupt should be triggered
    // when the counter reaches 2/2.3*0xffff=0xde9a.
    OCR3AH = 0xde;
    OCR3AL = 0x9a;
    // Enable this interrupt
    ETIMSK |= 1<<OCIE3A;
    // THE ADVANTAGE of the CTC over the solution for ex. 23 is that the interval
    // can be adjusted more precisely. In the previous mode you loose the time
    // that elapses between the moment the interrupt is triggered and the moment
    // the timer registers are reset.

    while (1) {
        if (toggle) {
            toggle = 0;
            write_led(0x01);
        }
        else {
            toggle = 1;
            write_led(0x00);
        }
        pause(10);
    }

    return 0;
}
```

Solution 3.7 In my case, i measured an execution time of 0.25 ms without `printf()` and 1.2 ms with `printf()`.

Solution 3.9

```
#include <hardware/btn-hardware.h>
#include <dev/irqreg.h>
#include <stdio.h>                  // freopen
#include <io.h>                     // _ioctl
#include <dev/usartavr.h>           // NutRegisterDevice, APP_UART, UART_SETSPEED
#include <sys/timer.h>

// COMPUTE ADC values corresponding to 1 and 2 Volts:
// If battery voltage is 1V, the BAT_SENSE signal is 0.5V.
// The reference voltage is 3.3V and corresponds to the ADC value 1024.
// Therefore 0.5V corresponds to an ADC value of 1024/3.3*0.5=155.
// A battery voltage is 2V, ADC value is 310.
#define BAT_1_VOLT 155
#define BAT_2_VOLT 310

int adc_done = 0;
int battery_voltage = 0;

void shortpause(u_short duration)
{
    u_short i;
    for (i=0;i<duration;i++) {
    }
}

void pause(u_short duration)
{
    u_short i;
    for (i=0;i<duration;i++) {
        shortpause(0xffff);
    }
}

void write_led(u_char value)
{
    volatile u_char * pointer;
    u_char dummy;

    pointer  = (u_char *) ( ((u_short)value) << 8);
    dummy    = *pointer;

    sbi(PORTB, 5);
    asm volatile  ("nop" ::);
    cbi(PORTB, 5);
}

int get_battery_volt(void)
{
    int result;

    ADMUX |= 1<<MUX0;
    ADMUX |= 1<<MUX1;
    ADCSRA |= 1<<ADPS0;
    ADCSRA |= 1<<ADPS1;
    ADCSRA |= 1<<ADPS2;
    ADCSRA |= 1<<ADEN;
    ADCSRA |= 1<<ADSC;
    while (ADCSRA & (1<<ADSC)) ;

    result = ADCL;
    result |= ADCH << 8;

    return result;
}

static void timer3IRQ(void *arg)
{
    battery_voltage = get_battery_volt();

    if (battery_voltage < BAT_1_VOLT) {
       write_led(0x02);
    }
    else {
        if (battery_voltage < BAT_2_VOLT) {
           write_led(0x04);
        }
        else {
           write_led(0x08);
        }
    }
    // Reset the counter to non-zero value, see expl. in main routine.
    TCNT3H = 0x21;
    TCNT3L = 0x64;
    adc_done = 1;
}

int init_stdout(void)
{
    u_long baud = 57600;

    sbi( PORTD, 2);
    NutRegisterDevice(&APP_UART, 0, 0);
    freopen(APP_UART.dev_name, "r+", stdout);
    _ioctl(_fileno(stdout), UART_SETSPEED, &baud);
    return 1;
}

int main(void)
{
    init_stdout();
    printf("Hello world!\n");
    DDRB |= 1<<DDB5;

    NutRegisterIrqHandler(&sig_OVERFLOW3, timer3IRQ, 0);
    // 16 bit timer without prescaler (clock frequency 7.3MHz)
    // -> overflows once every 0xffff*(1/7.3E6)s=9ms
    // For an overflow every 2s, prescaler should be
    // 2s/9ms = 223. The closest value is 256 (see table on page 135).
    // This gives an overflow every 2.3s. This could be adjusted by
    // setting the counter value to 0.3/2.3*0xfffff = 0x2164 after
    // every overflow, thus at the end of the timer interrupt routine
    TCCR3B |= 1<<CS32;
    ETIMSK |= 1<<TOIE3;

    while (1) {
        while (adc_done == 0) {
            pause(1);
        }
        printf("Battery voltage is %d units\n",battery_voltage);
        adc_done = 0;
    }

    return 0;
}
```

Solution 3.10 There are a few different cases to consider here:

`battery_voltage_millivolt=(3300*battery_voltage_raw)/512;`

This does not work. in my case `battery_voltage_raw` is 380 units, thus $3300 \cdot 380 = 1254000$ is far larger than what can be put in an int (16 bit) with a maximal value of +32767. Signed int is no better, the maximum is +65535. In contrast a signed long overflows at +2147483647, which is sufficient for this case.

`battery_voltage_millivolt=3300*(battery_voltage_raw/512);`

This also does not work, because $380/512 = 0$ (its integers!).

Here is the final solution:

```
int battery_voltage_raw, battery_voltage_millivolt;
battery_voltage_millivolt = (3300*(long)battery_voltage_raw)/512;
```

Solution 3.11

```
#include <hardware/btn-hardware.h>
#include <dev/irqreg.h>
#include <stdio.h>                  // freopen
#include <io.h>                     // _ioctl
#include <dev/usartavr.h>           // NutRegisterDevice, APP_UART, UART_SETSPEED
#include <sys/timer.h>

// COMPUTE ADC values corresponding to 1 and 2 Volts:
// If battery voltage is 1V, the BAT_SENSE signal is 0.5V.
// The reference voltage is 3.3V and corresponds to the ADC value 1024.
// Therefore 0.5V corresponds to an ADC value of 1024/3.3*0.5=155.
// A battery voltage is 2V, ADC value is 310.
#define BAT_1_VOLT 155
#define BAT_2_VOLT 310

int adc_done = 0;
int battery_voltage = 0;

u_char temp_sreg;

void shortpause(u_short duration)
{
    u_short i;
    for (i=0;i<duration;i++) {
    }
}

void pause(u_short duration)
{
    u_short i;
    for (i=0;i<duration;i++) {
        shortpause(0xffff);
    }
}

void write_led(u_char value)
{
    volatile u_char * pointer;
    u_char dummy;

    pointer  = (u_char *) ( ((u_short)value) << 8);
    dummy    = *pointer;

    sbi(PORTB, 5);
    asm volatile  ("nop" ::);
    cbi(PORTB, 5);
}

int get_battery_volt(void) {

    int result;

    ADMUX |= 1<<MUX0;
    ADMUX |= 1<<MUX1;

    ADCSRA |= 1<<ADPS0;
    ADCSRA |= 1<<ADPS1;
    ADCSRA |= 1<<ADPS2;

    ADCSRA |= 1<<ADEN;
    ADCSRA |= 1<<ADSC;
    while (ADCSRA & (1<<ADSC)) ;

    result = ADCL;
    result |= ADCH << 8;

    return result;
}

static void timer3IRQ(void *arg)
{
    battery_voltage = get_battery_volt();

    if (battery_voltage < BAT_1_VOLT) {
       write_led(0x02);
    }
    else {
        if (battery_voltage < BAT_2_VOLT) {
           write_led(0x04);
        }
        else {
           write_led(0x08);
        }
    }
    // Reset the counter to non-zero value, see expl. in main routine.
    TCNT3H = 0x21;
    TCNT3L = 0x64;
    adc_done = 1;
}

int init_stdout(void)
{
    u_long baud = 57600;

    sbi( PORTD, 2);
    NutRegisterDevice(&APP_UART, 0, 0);
    freopen(APP_UART.dev_name, "r+", stdout);
    _ioctl(_fileno(stdout), UART_SETSPEED, &baud);
    return 1;
}

void EnterCritical(void)
{
    temp_sreg = SREG;
    cli();
}

void ExitCritical(void)
{
    SREG = temp_sreg;
    // an explicit sei(); is not necessary, since the I flag is
    // already set if it had been before the previous EnterCritical();
}

int main(void)
{
    int battery_voltage_volt;
    init_stdout();
    printf("Hello world!\n");
    DDRB |= 1<<DDB5;

    NutRegisterIrqHandler(&sig_OVERFLOW3, timer3IRQ, 0);
    // 16 bit timer without prescaler (clock frequency 7.3MHz)
    // -> overflows once every 0xffff*(1/7.3E6)s=9ms
    // For an overflow every 2s, prescaler should be
    // 2s/9ms = 223. The closest value is 256 (see table on page 135).
    // This gives an overflow every 2.3s. This could be adjusted by
    // setting the counter value to 0.3/2.3*0xfffff = 0x2164 after
    // every overflow, thus at the end of the timer interrupt routine
    TCCR3B |= 1<<CS32;
    ETIMSK |= 1<<TOIE3;

    EnterCritical();
    while (1) {
        while (adc_done == 0) { //adc_done is shared
            ExitCritical();
            // pause is not necessary
            EnterCritical();
        }
        battery_voltage_volt = (3300*(long)battery_voltage)/512; //battery_voltage is shared
        printf("Battery voltage is %d millivolts\n",battery_voltage_volt); //battery_voltage is shared
        adc_done = 0; //adc_done is shared
    }
    ExitCritical();

    return 0;
}
```

Solution 3.12 In line 7, the value for the LEDs is put on the address bus. It is assumed that it remains there until the latch is disabled in line 11. This is not the case if between lines 7 and 11 an interrupt occurs. Thus an `EnterCritical()` should be inserted before line 7 and an `ExitCritical()` after line 11.

```
01 void write_led(u_char value)
02 {
03    volatile u_char * pointer;
04    u_char dummy;
05
06    pointer  = (u_char *) ( ((u_short)value) << 8);
07    dummy    = *pointer;
08
09    sbi(PORTB, 5);
10    asm volatile  ("nop" ::);
11    cbi(PORTB, 5);
12 }
```

Solution 5.1

```
#include <sys/thread.h>
#include <hardware/btn-hardware.h>
#include <led/btn-led.h>

THREAD(my_thread, arg)
{
    for (;;) {
        btn_led_clear(LED0);
        btn_led_set(LED1);
        NutThreadYield(); // second yield to add (then both LEDs are on)
    }
}

int main(void)
{
    // hardware init
    btn_hardware_init();
    btn_led_init(0);


    NutThreadCreate("my_thread",my_thread,0,192);
    for (;;) {
        btn_led_clear(LED1);
        btn_led_set(LED0);
        NutThreadYield(); // first yield to add (then only red LED is on)
    }
    return 0;
}
```

Solution 5.5 The terminal output should look like this:

```
my_thread is alive
main is alive
my_thread is alive
main is alive
my_thread is alive
main is alive
my_thread is alive
main is alive
my_thread is alive
main is alive
...
```

You would expect for both exercises the same output, that of exercise 5.1. The reason for the deviating behavior is that the mechanism that wakes up threads after a sleep is buggy:

1. `NutSleep` puts the threads in the sleep queue, AFTER all threads of higher or equal priority.
2. When threads are woken up, the threads are put in the run queue, BEFORE all threads of lower or equal priority.

Thus if two threads have the same priority and are woken up at the same time, their order gets reversed. The probelm does not occur when the threads have different priorities or are woken up at different times.

Both threads are woken up at the same time, because `NutSleep` has a granularity of approximately 64 milliseconds. We have seen in the previous chapter that a printf (with such a short string) takes about 1 millisecond, thus both threads go to sleep and are woken up in the same 64 milliseconds time slot.

Sample code:

```
#include <sys/thread.h>
#include <sys/timer.h>
#include <hardware/btn-hardware.h>
#include <led/btn-led.h>
#include <stdio.h>                 // freopen
#include <io.h>                    // _ioctl
#include <dev/usartavr.h>          // NutRegisterDevice, APP_UART, UART_SETSPEED

int init_stdout(void)
{
    u_long baud = 57600;

    sbi( PORTD, 2);
    NutRegisterDevice(&APP_UART, 0, 0);
    freopen(APP_UART.dev_name, "r+", stdout);
    _ioctl(_fileno(stdout), UART_SETSPEED, &baud);
    return 1;
}

THREAD(my_thread, arg)
{
    NutThreadSetPriority(20);
    for (;;) {
        printf("my_thread is alive\n");
        NutSleep(1000);
    }
}

int main(void)
{
    // hardware init
    btn_hardware_init();
    btn_led_init(0);

    init_stdout();

    NutThreadCreate("my_thread",my_thread,0,192);
    for (;;) {
        printf("main is alive\n");
        NutSleep(1000);
    }
    return 0;
}
```

Solution 5.7

```
#include <stdio.h>
#include <dev/usartavr.h>
#include <sys/thread.h>
#include <sys/timer.h>
#include <sys/tracer.h>
#include <hardware/btn-hardware.h>
#include <sys/osdebug.h>

#include <terminal/btn-terminal.h>

int init_stdout(void)
{
    u_long baud = 57600;

    sbi( PORTD, 2);
    NutRegisterDevice(&APP_UART, 0, 0);
    freopen(APP_UART.dev_name, "r+", stdout);
    _ioctl(_fileno(stdout), UART_SETSPEED, &baud);
    return 1;
}

THREAD(my_thread, arg)
```

```
{
    for (;;) {
        printf("%s is alive\n",runningThread->td_name);
        NutSleep(1000);
    }
}

void create(char * arg)
{
    char name[20];
    int val;
    // strange behavior here: typing "create name" does not work, but "create name " does!?
    val = sscanf(arg,"%s",name);
    if (val==1) {
        printf("Create a thread with name %s\n",name);
        if (0 == NutThreadCreate(name,my_thread,0,292)) {
            printf("FAILED!\n");
        }
        else {
            printf("SUCCESFUL!\n");
        }
    }
}

int main(void)
{
    // hardware init
    btn_hardware_init();

    init_stdout();

    btn_terminal_init(stdout, "[bt-cmd@btnode]$");
    btn_terminal_register_cmd("create",create);
    btn_terminal_run(BTN_TERMINAL_NOFORK, 0);
    return 0;
}
```

Solution 5.8

```
#include <stdio.h>
#include <dev/usartavr.h>
#include <sys/thread.h>
#include <sys/timer.h>
#include <sys/tracer.h>
#include <hardware/btn-hardware.h>
#include <sys/osdebug.h>

#include <terminal/btn-terminal.h>

int init_stdout(void)
{
    u_long baud = 57600;

    sbi( PORTD, 2);
    NutRegisterDevice(&APP_UART, 0, 0);
    freopen(APP_UART.dev_name, "r+", stdout);
    _ioctl(_fileno(stdout), UART_SETSPEED, &baud);
    return 1;
}

THREAD(my_thread, arg)
{
    int sleeptime = *(int*)arg;
    for (;;) {
        printf("%s is alive, will sleep for %d seconds\n",runningThread->td_name,sleeptime);
        NutSleep((u_long)1000*sleeptime);
    }
}

void create(u_char * arg)
{
    static int sleeptime = 1;
    char name[20];
    int val;
    val = sscanf(arg,"%s",name);
    if (val==1) {
        printf("Create a thread with name %s and sleeptime %d\n",name,sleeptime);
        if (0 == NutThreadCreate(name,my_thread,&sleeptime,292)) {
            printf("FAILED!\n");
        }
        else {
            printf("SUCCESFUL!\n");
            sleeptime++;
        }
    }
}

int main(void)
{
    // hardware init
    btn_hardware_init();

    init_stdout();

    btn_terminal_init(stdout, "[bt-cmd@btnode]$");
    btn_terminal_register_cmd("create",create);
    btn_terminal_run(BTN_TERMINAL_NOFORK, 0);
    return 0;
}
```

Solution 5.9

```
#include <stdio.h>
#include <dev/usartavr.h>
#include <sys/thread.h>
#include <sys/timer.h>
#include <sys/tracer.h>
#include <hardware/btn-hardware.h>
#include <sys/osdebug.h>
#include <terminal/nut-cmds.h>

#include <terminal/btn-terminal.h>

int init_stdout(void)
{
    u_long baud = 57600;

    sbi( PORTD, 2);
    NutRegisterDevice(&APP_UART, 0, 0);
    freopen(APP_UART.dev_name, "r+", stdout);
    _ioctl(_fileno(stdout), UART_SETSPEED, &baud);
    return 1;
}

THREAD(my_thread, arg)
{
// IF THE variable dummy_str is initialized AND USED, more stack is used
//    char  dummy_str[20];
    int sleeptime = *(int*)arg;
//    sprintf(dummy_str,"hello world\n");
    for (;;) {
        printf("%s is alive, will sleep for %d seconds\n",runningThread->td_name,sleeptime);
        NutSleep(1000*sleeptime);
    }
}

void create(u_char * arg)
{
    static int sleeptime = 1;
    int stacksize;
    char name[20];
    int val;
    val = sscanf(arg,"%s%d",name,&stacksize);
    if (val==2) {
        printf("Create a thread with name %s and sleeptime %d\n",name,sleeptime);
        if (0 == NutThreadCreate(name,my_thread,&sleeptime,stacksize)) {
            printf("FAILED!\n");
        }
        else {
            printf("SUCCESFUL!\n");
            sleeptime++;
        }
    }
}

int main(void)
{
    // hardware init
    btn_hardware_init();
    init_stdout();

    btn_terminal_init(stdout, "[bt-cmd@btnode]$");
    btn_terminal_register_cmd("create",create);
    nut_cmds_register_cmds();
    btn_terminal_run(BTN_TERMINAL_NOFORK, 0);
    return 0;
}
```

Solution 5.12

```
#include <stdio.h>
#include <dev/usartavr.h>
#include <sys/thread.h>
#include <sys/timer.h>
#include <sys/tracer.h>
#include <sys/event.h>
#include <hardware/btn-hardware.h>
#include <led/btn-led.h>

HANDLE event;

int init_stdout(void)
{
    u_long baud = 57600;

    sbi( PORTD, 2);
    NutRegisterDevice(&APP_UART, 0, 0);
    freopen(APP_UART.dev_name, "r+", stdout);
    _ioctl(_fileno(stdout), UART_SETSPEED, &baud);
    return 1;
}

THREAD(my_thread, arg)
{
    int count = 0;
    for (;;) {
        NutEventWait(&event, NUT_WAIT_INFINITE);
        count++;
        printf("myThread has received event no. %d\n",count);
    }
}

int main(void)
{
    init_stdout();
    NutEventPost(&event);
    printf("main posts an event\n");
    NutEventPost(&event);
    printf("main posts an event\n");
    NutThreadCreate("myThread",my_thread,0,192);
    printf("main enters endless loop\n");
    for (;;)
        NutThreadYield();
    return 0;
}
```

Solution 5.13

```
#include <stdio.h>
#include <dev/usartavr.h>
#include <sys/thread.h>
#include <sys/timer.h>
#include <sys/tracer.h>
#include <sys/event.h>
#include <hardware/btn-hardware.h>
#include <led/btn-led.h>
#include <string.h>

HANDLE event;

void shortpause(u_short duration)
{
    u_short i;
    for (i=0;i<duration;i++) {
    }
}
```

```
void pause(u_short duration)
{
    u_short i;
    for (i=0;i<duration;i++) {
        shortpause(0xffff);
    }
}

int init_stdout(void)
{
    u_long baud = 57600;

    sbi( PORTD, 2);
    NutRegisterDevice(&APP_UART, 0, 0);
    freopen(APP_UART.dev_name, "r+", stdout);
    _ioctl(_fileno(stdout), UART_SETSPEED, &baud);
    return 1;
}

THREAD(my_thread, arg)
{
    int count = 0;
    if (strncmp("A",runningThread->td_name,1)==0) {
//        NutThreadSetPriority(10);
    }
    for (;;) {
        NutEventWait(&event, NUT_WAIT_INFINITE);
        count++;
        printf("Thread %s has received event no. %d\n",runningThread->td_name,count);
        pause(12);
    }
}

int main(void)
{
    int count = 7;
    init_stdout();
    NutThreadCreate("A",my_thread,0,192);
    NutThreadCreate("B",my_thread,0,192);
    while (count > 0) {
        NutEventPost(&event);
//        printf("main posts an event\n");
        count--;
    }
    printf("main enters endless loop\n");
    pause(12);
    for (;;)
        NutThreadYield();
    return 0;
}
```

Solution 5.14

The output received is:

```
main posts an event
main posts an event
main enters endless loop
myThread has received event no. 1
```

`myThread` receives only 1 event, even though main had posted an event twice before starting `myThread`. Thus we see that the event-queue remembers that an event was posted when no one waits for it, but it does not remember how many events have been posted. The implementation of the event-queues is so that the event-queue enters the 'signaled' state when an event is posted and nobody waits for it, but there is no counter of such events.

Sample Code

```
#include <stdio.h>
#include <dev/usartavr.h>
#include <sys/thread.h>
#include <sys/timer.h>
#include <sys/tracer.h>
#include <sys/event.h>
#include <hardware/btn-hardware.h>
#include <led/btn-led.h>
```

```
HANDLE event;

int init_stdout(void)
{
    u_long baud = 57600;

    sbi( PORTD, 2);
    NutRegisterDevice(&APP_UART, 0, 0);
    freopen(APP_UART.dev_name, "r+", stdout);
    _ioctl(_fileno(stdout), UART_SETSPEED, &baud);
    return 1;
}

THREAD(my_thread, arg)
{
    int count = 0;
    for (;;) {
        NutEventWait(&event, NUT_WAIT_INFINITE);
        count++;
        printf("myThread has received event no. %d\n",count);
    }
}

int main(void)
{
    init_stdout();
    NutEventPost(&event);
    printf("main posts an event\n");
    NutEventPost(&event);
    printf("main posts an event\n");
    NutThreadCreate("myThread",my_thread,0,192);
    printf("main enters endless loop\n");
    for (;;)
        NutThreadYield();
    return 0;
}
```

Solution 5.16

The output received is:

```
Thread A has received event no. 1
Thread B has received event no. 1
Thread A has received event no. 2
Thread B has received event no. 2
Thread A has received event no. 3
Thread B has received event no. 3
main enters endless loop
Thread A has received event no. 4
```

Thus we see that every event is received ONLY by one thread, even though two threads are waiting. Since both threads have the same priority, they are served in turns.

When line 80 `NutThreadSetPriority` is included, then the output is:

```
Thread A has received event no. 1
Thread A has received event no. 2
Thread A has received event no. 3
Thread A has received event no. 4
Thread A has received event no. 5
Thread A has received event no. 6
Thread A has received event no. 7
main enters endless loop
```

Thus we see that thread priorities DO play a role.

Note that the calls to the pause function are a quick hack that leads to a readable terminal output (remember that `printf` implicitely does a `NutThreadYield`, see exercise 5.1).

Sample Code

```
#include <stdio.h>
#include <dev/usartavr.h>
#include <sys/thread.h>
#include <sys/timer.h>
```

```
#include <sys/tracer.h>
#include <sys/event.h>
#include <hardware/btn-hardware.h>
#include <led/btn-led.h>
#include <string.h>

HANDLE event;

void shortpause(u_short duration)
{
    u_short i;
    for (i=0;i<duration;i++) {
    }
}

void pause(u_short duration)
{
    u_short i;
    for (i=0;i<duration;i++) {
        shortpause(0xffff);
    }
}

int init_stdout(void)
{
    u_long baud = 57600;

    sbi( PORTD, 2);
    NutRegisterDevice(&APP_UART, 0, 0);
    freopen(APP_UART.dev_name, "r+", stdout);
    _ioctl(_fileno(stdout), UART_SETSPEED, &baud);
    return 1;
}

THREAD(my_thread, arg)
{
    int count = 0;
    if (strncmp("A",runningThread->td_name,1)==0) {
//        NutThreadSetPriority(10);
    }
    for (;;) {
        NutEventWait(&event, NUT_WAIT_INFINITE);
        count++;
        printf("Thread %s has received event no. %d\n",runningThread->td_name,count);
        pause(12);
    }
}

int main(void)
{
    int count = 7;
    init_stdout();
    NutThreadCreate("A",my_thread,0,192);
    NutThreadCreate("B",my_thread,0,192);
    while (count > 0) {
        NutEventPost(&event);
//        printf("main posts an event\n");
        count--;
    }
    printf("main enters endless loop\n");
    pause(12);
    for (;;)
        NutThreadYield();
    return 0;
}
```

Solution 6.6

```
#include <io.h>
#include <stdio.h>
#include <dev/usartavr.h>
#include <sys/thread.h>
#include <sys/timer.h>
#include <sys/tracer.h>
#include <hardware/btn-hardware.h>
#include <led/btn-led.h>
#include <terminal/btn-terminal.h>

int init_stdout(void)
{
    u_long baud = 57600;
    sbi( PORTD, 2);
    NutRegisterDevice(&APP_UART, 0, 0);
    freopen(APP_UART.dev_name, "r+", stdout);
    _ioctl(_fileno(stdout), UART_SETSPEED, &baud);
    return 1;
}

THREAD(ledthread, arg)
{
    for (;;) {
        btn_led_clear(LED1);
        btn_led_set(LED0);
        NutSleep(500);
        btn_led_clear(LED0);
        btn_led_set(LED1);
        NutSleep(500);
    }
}

int main(void)
{
    // hardware init
    btn_hardware_init();
    btn_led_init(0);
    init_stdout();
    NutThreadCreate("LedThr",ledthread,0,192);
    btn_terminal_init(stdout, "[bt-cmd@btnode]$");
    btn_terminal_register_cmd("trace",NutTraceTerminal);
    btn_terminal_run(BTN_TERMINAL_NOFORK, 0);

    return 0;
}
```

Solution 7.1 The Bluetooth device address can be found on a label attached to the BTnode and consists of 6 bytes (e.g. `00:04:3F:00:00:4B`).

Solution 7.2

```
struct bt_hci_pkt_cmd pkt;   //
pkt.type=0x01;              //HCI command packet
pkt.payload[0]=0x01;        //first byte of OpCode
pkt.payload[1]=0x04;        //second byte of OpCode
pkt.payload[2]=0x05;        //total length of parameters
pkt.payload[3]=0x33;        //GIAC
pkt.payload[4]=0x8b;        //GIAC
pkt.payload[5]=0x9e;        //GIAC
pkt.payload[6]=0x05;        //inquiry length 5*1.28s = 6.4 seconds
pkt.payload[7]=0x05;        //maximum number of devices
```

Solution 7.3

```
// send an inquiry command ...
// and use the Btstack thread to receice the answers
#include <sys/tracer.h>
#include <hardware/btn-hardware.h>
#include <terminal/btn-terminal.h>
#include <stdio.h> // freopen
#include <dev/usartavr.h> // NutRegisterDevice, APP_UART, UART_SETSPEED
#include <led/btn-led.h> // needed! (together with btn_led_init(0);), maybe a bug ???
#include <bt/bt_hci_dispatch.h> // for the setWaitQueue command
#include <sys/event.h>  // for NutEventWait and NUT_WAIT_INFINITE
#include <bt/bt_hci_cmds.h> // for sending hci commands

#define HCI_COMMAND_DATA_PACKET        0x01
#define HCI_OGF_LINK_CONTROL        0x01
#define HCI_OCF_LC_INQUIRY                0x01
#define BT_HCI_HANDLE_INVALID 0xFFFF

struct btstack* stack;

void init_stdout(void) {
u_long baud = 57600;
btn_hardware_init();
NutRegisterDevice(&APP_UART, 0, 0);
freopen(APP_UART.dev_name, "r+", stdout);
```

```
_ioctl(_fileno(stdout), UART_SETSPEED, &baud);
}

//print a single bluetooth device address to the terminal
void print_bt_addr(bt_addr_t addr) {
      printf("%.2x:%.2x:%.2x:%.2x:%.2x:%.2x", addr[5],addr[4],addr[3],addr[2],addr[1],addr[0]);
}

//print the number of found devices and their addresses
void print_inq_result(struct bt_hci_cmd_response wcmd) {
    int i;
    printf("Devices: %li\n", wcmd.response);
    if (wcmd.response<0) {
      wcmd.response=0;
    } else {
      printf("Device         bt_addr \n");
    }
    for (i=0; i<wcmd.response; i++) {
        printf("[%d]: ", i);
        print_bt_addr(   (((struct bt_hci_inquiry_result*)(wcmd.ptr)) + i)->bdaddr   );
        printf(" \n");
    }
}

void inquiry (char* arg){

//**************** packet construction*****************************

struct bt_hci_pkt_cmd pkt;

pkt.type=HCI_COMMAND_DATA_PACKET;
pkt.payload[0]=HCI_OCF_LC_INQUIRY;
pkt.payload[1]=HCI_OGF_LINK_CONTROL<<2;
//cmd length = 5 bytes
pkt.payload[2]=0x05;
//General Inquiry Access Code (GIAC)
pkt.payload[3]=0x33;
pkt.payload[4]=0x8b;
pkt.payload[5]=0x9e;
// waiting time for the inquiry to complete
// ----> 5 * 1.28 s = 6.4 s
pkt.payload[6]=0x05;
// maximum number of responding devices
pkt.payload[7]=0x05;

//*************** prepare and register cmd_response-structure********

struct bt_hci_cmd_response wcmd;

//array for the storage of the answers of max. 10 devices
struct bt_hci_inquiry_result inquiry_result[10];

//initialize the cmd_response-structure
wcmd.ogfocf= ((HCI_OCF_LC_INQUIRY<<8)|(HCI_OGF_LINK_CONTROL<<2));
wcmd.cmd_handle= BT_HCI_HANDLE_INVALID;
wcmd.response=0;
wcmd.ptr= &inquiry_result;
wcmd.block=0;

//register the wcmd in the WaitQueue of the running stack
_bt_hci_setWaitQueue(stack,&wcmd);

//*************** send packet, wait and readout the results********

_bt_hci_send_pkt(stack,(u_char*)&pkt);
printf("Starting inquiry .....\n");
NutEventWait(&(wcmd.block),NUT_WAIT_INFINITE);
printf("Inquiry done! \n");

print_inq_result(wcmd);
}

int main(void) {
btn_hardware_init();
btn_led_init(0);
init_stdout();

// bluetooth module on (takes a while)
btn_hardware_bt_on();

// Start the stack and let the initialization begin
```

```
stack = bt_hci_init(&BT_UART);

btn_terminal_init(stdout, "[es200X]$");
btn_terminal_register_cmd("inquiry", inquiry);
btn_terminal_register_cmd("trace",NutTraceTerminal);
btn_terminal_run(BTN_TERMINAL_NOFORK, 0);
return 0;
}
```

Solution 7.4 You can clearly identify a `CommandStatusEvent`, several `InquiryResultEvents` as well as a final `InquiryCompleteEvent`.

Solution 7.6

```
//        sending a string message within an acl-packet
/*
 * Copyright (C) 2000-2006 by ETH Zurich
 *
 * Redistribution and use in source and binary forms, with or without
 * modification, are permitted provided that the following conditions
 * are met:
 *
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 * OF USE, DATA, OR PROFITS; OR BUSINESS INTERRUPTION) HOWEVER CAUSED
 * AND ON ANY THEORY OF LIABILITY, WHETHER IN CONTRACT, STRICT LIABILITY,
 * OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY OUT OF
 * THE USE OF THIS SOFTWARE, EVEN IF ADVISED OF THE POSSIBILITY OF
 * SUCH DAMAGE.
 *
 * For additional information see http://www.btnode.ethz.ch/
 *
 * $Id: ex7.6-listing.c,v 1.2 2007/01/17 19:21:30 yuecelm Exp $
 *
 */

/*!
 * $Log: ex7.6-listing.c,v $
 * Revision 1.2  2007/01/17 19:21:30  yuecelm
 * minor changes and updates after reviewing the whole tutorial
 *
 * Revision 1.1  2007/01/16 13:07:52  beutel
 * first try with all new solutions and marcs stuff
 *
 * Revision 1.3  2006/05/19 15:02:08  cmoser79
 * final changes to chapter 6 (Clemens)
 *
 * Revision 1.43  2006/04/06 08:52:10  kevmarti
 * removed 'log_cmds_register_cmds()' function (registering is now done in 'log_cmds_init()')
 *
 * Revision 1.42  2006/04/05 12:56:21  kevmarti
 * adjusted call to 'log_init()'
 *
 * Revision 1.41  2006/04/05 12:47:37  kevmarti
 * Added call to log_cmds_init()
 *
 * Revision 1.40  2006/04/05 10:44:22  kevmarti
 * terminal cmds for logging moved from 'debug/logging.c' to 'terminal/log-cmds.c'
 *
 * Revision 1.39  2006/04/05 10:05:48  beutel
 * *** empty log message ***
 *
 * Revision 1.38  2006/04/05 05:29:36  dyerm
 * fixed reading of bt version and features for the fancy header
 *
 * Revision 1.37  2006/03/29 01:15:00  olereinhardt
 *
 * Changed signedness of strings in order to compile with avr-gcc 4.0.2
 *
 * Revision 1.36  2006/03/24 14:44:50  dyerm
 * removed obsolete bt_acl_com
 *
 * Revision 1.35  2006/03/23 17:13:57  beutel
 * added version, features and name to bt-cmd
 *
 * Revision 1.34  2006/03/23 17:12:39  beutel
 * added version, features and name to bt-cmd
 *
 * Revision 1.33  2006/03/23 07:22:24  dyerm
 * Merged changes from multihop_merge branch. See individual changes on
 * multihop_merge branch. See Changelog for summary of changes.
 *
 */

/**
 * \example bt-cmd/bt-cmd.c
 *
 * \date 2004/06/18
 *
 * \author Martin Hinz <btnode@hinz.ch>
 * \author Jan Beutel <j.beutel@ieee.org>
 *
 * Example application to show the use of the bt stack and the simple but
 * powerful terminal interface.
 */

#include <stdio.h>
#include <dev/usartavr.h>
#include <sys/heap.h>
#include <sys/timer.h>

#include <hardware/btn-hardware.h>

#include <bt/bt_hci_cmds.h>

#include <terminal/btn-terminal.h>
#include <terminal/btn-cmds.h>
#include <terminal/bt-cmds.h>
#include <terminal/nut-cmds.h>
#include <terminal/log-cmds.h>

#include <led/btn-led.h>
#include <debug/logging.h>

#include "program_version.h"
#define CVS_VERSION "$Id: ex7.6-listing.c,v 1.2 2007/01/17 19:21:30 yuecelm Exp $"

struct btstack* stack;
extern u_char _bt_hci_debug_uart;

//sending a text message on a certain channel with a certain connection handle
void transmit (char* arg){

        int handle, channel,i;
        u_char message[20];
        //set empty message
        for (i=0;i<=19;i++)
                message[i]=' ';

        //dont separate single words in "message" with spaces,
        //BUT: leave space after end of "message",
        //(otherwise bluetooth module may be re-booted)
        sscanf(arg, "%u%u%s", &handle, &channel, message);

        //define a packet:  5 bytes for hci-packet-header,
        //4 bytes for L2CAP-packet header and  20 bytes payload
        u_char hci_acl_pkt[29];

        //the following bytes are set by the bt_hci_send_acl_pkt-function:
        //hci_acl_pkt[0] type
        //hci_acl_pkt[1] con handle
        //hci_acl_pkt[2] con handle + flags
        //hci_acl_pkt[3] flags + data length
        //hci_acl_pkt[4] data length
        hci_acl_pkt[5]=(u_char)(20 & 0xFF);
        hci_acl_pkt[6]=(u_char)((20>>8) & 0xFF);
        hci_acl_pkt[7]=(u_char)(channel & 0xFF);
        hci_acl_pkt[8]=(u_char)((channel>>8) & 0xFF);

        //attach the string message
        for(i=0;i<=18;i++)
                hci_acl_pkt[9+i]=message[i];

        //... and send the packet
        bt_hci_send_acl_pkt(stack,handle,2,0,24,(struct bt_hci_pkt_acl*)(hci_acl_pkt));

        printf("Message (%s) sent with handle %d, channel %d \n",message,handle,channel);
}


struct bt_hci_pkt_acl* receive(void *arg, struct bt_hci_pkt_acl *pkt, bt_hci_con_handle_t con_handle,
                               u_char pb_flag, u_char bc_flag, u_short len, u_long t_arrive)
{
        u_char* l2cap_hdr = pkt->payload;
        u_char* l2cap_data;
        u_short chan_id;

        chan_id = l2cap_hdr[2] | (l2cap_hdr[3] << 8);

        l2cap_data = &l2cap_hdr[4];

        printf("message received on channel %d: %s\n", chan_id, l2cap_data);
        return pkt;
}


/**
 * main function that initializes the hardware, led, terminal, bluetooth
 * and acl communication stack and registers some predefined commands.
 * Use tab-tab to see the registered commands once the program is running.
 */
int main(void)
{
          u_char acl_pkt[120];

    // serial baud rate
    u_long baud = 57600;
    u_long cpu_crystal;
    u_long nut_tick_freq;

    // hardware init
    btn_hardware_init();
    btn_led_init(1);

    // init app uart
    NutRegisterDevice(&APP_UART, 0, 0);
    freopen(APP_UART.dev_name, "r+", stdout);
    _ioctl(_fileno(stdout), UART_SETSPEED, &baud);

    // logging
    log_init();

    // hello world!
    printf("\n# --------------------------------------------------------");
    printf("\n# Welcome to BTnut (c) 2006 ETH Zurich\n");
    printf("# bt-cmd program version: %s\n", PROGRAM_VERSION);
    printf("# %s\n", CVS_VERSION);
    cpu_crystal = NutGetCpuClock();
    nut_tick_freq = NutGetTickClock();
    printf("# running @ %u.%04u MHz, NutFreq=%ul Hz\n",
           (int) (cpu_crystal / 1000000UL), (int) ((cpu_crystal - (cpu_crystal / 1000000UL) * 1000000UL) / 100),
        (int) nut_tick_freq);
    printf("# --------------------------------------------------------");
    printf("\nbooting Bluetooth module...\n");

    // bluetooth module on (takes a while)
    btn_hardware_bt_on();

    // verbose debug of all hci information
    //_bt_hci_debug_uart = 1;

    // Start the stack and let the initialization begin
    stack = bt_hci_init(&BT_UART);

    bt_hci_write_default_link_policy_settings(stack, BT_HCI_SYNC,
                                              BT_HCI_LINK_POLICY_ROLE_SWITCH |
                                                BT_HCI_LINK_POLICY_HOLD_MODE |
                                                BT_HCI_LINK_POLICY_SNIFF_MODE |
                                                BT_HCI_LINK_POLICY_PARK_STATE );
    bt_addr_t addr;
    struct bt_hci_local_version_result version;
    u_char features[8];
    u_char _bt_cmds_name[30];

    bt_hci_read_bt_addr(stack, BT_HCI_SYNC, addr);
    printf("Bluetooth MAC address: %.2x:%.2x:%.2x:%.2x:%.2x:%.2x\n", addr[5], addr[4], addr[3], addr[2], addr[1], addr[0]);
    bt_hci_read_local_version_information(stack, BT_HCI_SYNC, &version);
    printf("HCI version: %X %.4X %X %.4X %.4X\n", version.hciversion,
           version.hcirevision, version.lmpversion, version.manufacturername, version.lmpsubversion);
    bt_hci_read_local_supported_features(stack, BT_HCI_SYNC, features);
    printf("LMP features: %.2X %.2X %.2X %.2X %.2X %.2X %.2X %.2X\n",
           features[0], features[1], features[2], features[3], features[4], features[5], features[6], features[7]);
    bt_hci_read_local_name(stack, BT_HCI_SYNC, _bt_cmds_name, sizeof(_bt_cmds_name));
    printf("Local name: '%s'\n", _bt_cmds_name);

    // give hint
    printf("hit tab twice for a list of commands\n\r");

    // terminal init
    char prompt[20];
    sprintf(prompt, "[bt-cmd@%.2x:%.2x]$", addr[1], addr[0]);
    btn_terminal_init(stdout, prompt);
    bt_cmds_init(stack);
    bt_cmds_register_cmds();
    btn_cmds_register_cmds();
    nut_cmds_register_cmds();
    log_cmds_init(stdout);

    bt_hci_register_acl_cb(stack, receive, (struct bt_hci_pkt_acl*)acl_pkt, NULL);

    btn_terminal_register_cmd("transmit",transmit);
    // terminal mode
    btn_terminal_run(BTN_TERMINAL_NOFORK, 0);

    return 0;
}
```

Solution 8.6

```
//solution to all programming exercises of chapter 7
#include <stdio.h>
#include <string.h>
#include <io.h>
#include <stdlib.h>
#include <dev/usart.h>
#include <dev/usartavr.h>
#include <bt/bt_hci_cmds.h>
#include <bt/bt_l2cap.h>
#include <bt/bt_rfcomm.h>
#include <terminal/btn-terminal.h>
#include <terminal/btn-cmds.h>
#include <terminal/bt-cmds.h>
#include <terminal/nut-cmds.h>
#include <terminal/l2cap-cmds.h>
#include <terminal/rfcomm-cmds.h>
#include <led/btn-led.h>
#include <hardware/btn-hardware.h>
#include <sys/timer.h>
#include <string.h>
#include <stdio.h>
#include <debug/toolbox.h>

#include "program_version.h"


#define BT_L2CAP_HCI_PACKET_TYPE         (BT_HCI_PACKET_TYPE_DM1 | BT_HCI_PACKET_TYPE_DH1 | \
                                          BT_HCI_PACKET_TYPE_DM3 | BT_HCI_PACKET_TYPE_DH3)

FILE   *uart_terminal;
struct btstack* stack;
struct bt_l2cap_stack* l2cap_stack;
struct bt_rfcomm_stack* rfcomm_stack;
```

```
#define MIN_CREDITS 10
#define MAX_CREDITS 40

void rcv_cb(u_char dlci, u_char * payload, u_short len, void *arg)
{
    u_short idx;
    if (len > 0) {
        printf("\n");
        for (idx = 0; idx < len; idx++)
            printf("%c ", payload[idx]);
    }
}

void con_cb(u_char dlci, u_char type, void *arg)
{
    if (type == BT_RFCOMM_CONNECT) {
        printf("RFCOMM Connect on dlci %d...\n", dlci);
        bt_rfcomm_send_credits(dlci, MAX_CREDITS - BT_RFCOMM_DEF_CREDITS);
    } else {
        printf("RFCOMM Disconnect on dlci %d...\n", dlci);
    }
}

void line_cb(u_char dlci, u_char flags, void *arg)
{
    printf("rfcomm Line status has changed: dlci: %d, flags: %02x\n", dlci, flags);
}

void credit_cb(u_char dlci, u_char credits, void *arg)
{
    printf("rfcomm Credits running low for dlci %d. Credits remaining: %d\n", dlci, credits);
    printf("rfcomm Send new credits: %d\n", MAX_CREDITS - credits);
    bt_rfcomm_send_credits(dlci, MAX_CREDITS - credits);
}

//returns the 7bit ASCII value of a character
int character_value(char character)
{
        //Lookup table for 7bit ASCII code
    const char alphabet[128] = {'@', '@', '$', '@', '@', '@', '@', '@', '@', '@', '\n', '@', '@',
          '\r','@', '@','@', '_', '@', '@', '@', '@', '@','@', '@', '@', '@','@', '@', '@', '@',
          '@',' ', '!', '"', '#', '@', '%', '&', '\'', '(', ')','*', '+', ',', '-', '.', '/',
          '0', '1', '2', '3', '4', '5', '6', '7','8', '9', ':', ';', '<', '=', '>', '?', '@',
          'A', 'B', 'C', 'D', 'E', 'F', 'G', 'H', 'I', 'J', 'K', 'L', 'M', 'N', 'O', 'P', 'Q',
          'R', 'S','T', 'U', 'V', 'W', 'X', 'Y', 'Z', '@', '@', '@', '@', '@', '@', 'a','b',
          'c', 'd', 'e', 'f', 'g', 'h', 'i', 'j', 'k', 'l', 'm', 'n', 'o','p', 'q', 'r', 's',
          't', 'u', 'v', 'w', 'x', 'y', 'z', '@', '@', '@','@', '@'};
    int i;

    for(i=0;i<128;i++){
        if(character == alphabet[i]){
            return i;
        }
    }
    return -1;                              //no valid character
}

//convert binary to integer
int bin2int(char * binary)
{
    int i;
    int sum = 0;
    int length;

    length = strlen(binary);
    for(i=0;i<length;i++){
        if(binary[i] == '1'){
            //sum += (int)pow((double)2,(double)(length-1-i));
            sum += 0x01<<(length-1-i);
        }
    }
    return sum;
}

void process_message(char * message_str, char * message)
{
    char buffer[8]="\0";
    int length;
    int i;
    int character = -1;
    char base[8]="\0";
    char carry[8]="\0";
    char rdbuffer[8]="\0";

    //init
    message_str[0] = '\0';

    length = strlen(message);
    if(length<=15){
        strcat(message_str, "00000");
    } else {
        if(length>160){
            length = 160;
        }
        strcat(message_str, "0000");
    }
    itoa(length, buffer, 16);        //convert integer to hex string
    strcat(message_str, buffer);

    for(i=0;i<=length;i++){
        if(i == length){
            if(base[0] != '\0'){
                character = bin2int(base);
                itoa(character, base, 16);
                if(strlen(base)==1){
                    base[1]=base[0];
                    base[0]='0';
                    base[2]='\0';
                }
                strcat(message_str, base);
            }
            break;
        }
        character = character_value(message[i]);
        if(character != -1){
            strcpy(buffer,"0000000");
            itoa(character, rdbuffer, 2);
            strcpy(buffer+7-strlen(rdbuffer), rdbuffer);
            if(i != 0 && i%8 !=0){
                strncpy(carry, buffer+7-i%8, i%8);
                carry[i%8] = '\0';
                strcat(carry, base);
                character = bin2int(carry);
                itoa(character, carry, 16);
                if(strlen(carry)==1){
                    carry[1]=carry[0];
                    carry[0]='0';
                    carry[2]='\0';
                }
                strcat(message_str, carry);
                strncpy(base, buffer, 7-i%8);
                base[7-i%8] = '\0';
            } else{
                strcpy(base, buffer);
            }
        } else{
            //ERROR: Not a valid character
        }
    }
}

char * process_phone_number(char * number_str, char * number)
{
    char buffer[3] = "\0";
    int length;

    //init
    number_str[0]='\0';

    if(*number == '+'){                 //skip '+' character in phone number
            number++;
        }
        length = strlen(number);
        if(length > 15){
                //invalid phone number
                return number_str;
        } else {
                itoa(length, buffer, 16);       //convert integer to hex string
        }
        strcat(number_str, buffer);
        strcat(number_str,"91");
    while(*number != '\0' && *(number+1) != '\0'){
        buffer[0] = *(number+1);
        buffer[1] = *number;
        buffer[2] = '\0';
        strcat(number_str,buffer);
        number += 2;
    }
    if(length % 2 != 0){
        buffer[0] = 'f';
        buffer[1] = *number;
        buffer[2] = '\0';
        strcat(number_str,buffer);
    }
    return number_str;
}

void send_sms_pdu_mode(char * number, char * message)
{
    char pdu[172]="\0";
    char buffer[13]="\0";
    int length;
    char rdbuffer[4]="\0";
    char number_str[19] = "\0";
    char message_str[147] = "\0";

    //message header
    strcat(pdu,"0025000");

    //process phone number
    if(process_phone_number(number_str, number)[0] == '\0'){
        //invalid phone number
        return;
    }
    strcat(pdu, number_str);

    //process message
    process_message(message_str, message);
    strcat(pdu, message_str);

    //pdu length
    length = strlen(pdu)/2-1;

    //line delimiter
    strcat(pdu, "\x1a");

    //at commands
    strcpy(buffer,"at+cmgs=");
    itoa(length, rdbuffer, 10);
    strcat(buffer, rdbuffer);
    strcat(buffer, "\r");
    //sms format: pdu
    bt_rfcomm_send(2, "at+cmgf=0\r", 10);
    NutSleep(1000);
    //sms command
    bt_rfcomm_send(2, buffer, strlen(buffer));
    NutSleep(1000);
    //message
    bt_rfcomm_send(2, pdu, strlen(pdu));
    //insert some delay to receive the send ok message
    NutSleep(5000);
}

void send_sms(char* arg)
{
    bt_addr_t BTaddr = {0x6d, 0x30, 0xc1, 0x9f, 0x11, 0x00};
    unsigned int addr[BD_ADDR_LEN];
    int i;
    char BTaddress[18] = "\0";
    char number[17] = "\0";
    char message[161] = "Greetings from the BTnode.";

    //interface for Bluetooth address input
    printf("\nEnter the Bluetooth address or the name of the sending phone: ");
    user_input(stdout, BTaddress, 18);

    //extracting the BTaddress
    if(sscanf(BTaddress, "%2x:%2x:%2x:%2x:%2x:%2x", &addr[5], &addr[4], &addr[3],
    &addr[2], &addr[1], &addr[0]) == 6) {
        for (i = 0; i < BD_ADDR_LEN; i++){
            BTaddr[i] = (u_char) addr[i];
        }
    }

    //connect
    if(bt_rfcomm_start_session(BTaddr, 0, 0)) return;
    NutSleep(1000);
    if(bt_rfcomm_connect(1, con_cb, rcv_cb, line_cb, credit_cb, 10, NULL)) return;
    NutSleep(1000);

    //general AT Commands
    bt_rfcomm_send(2, "at&f\r", 5);
    NutSleep(2000);
    bt_rfcomm_send(2, "at+cgmi\r", 8);
    NutSleep(1000);
    bt_rfcomm_send(2, "at+cgmm\r", 8);
    NutSleep(1000);
    bt_rfcomm_send(2, "at+cgsn\r", 8);
    NutSleep(1000);

    //user interface for SMS messaging
    printf("\nEnter the phone number of the recipient: ");
    user_input(stdout, number, 17);
    printf("\nEnter the message: ");
    user_input(stdout, message, 161);

    //send sms
    send_sms_pdu_mode(number, message);

    //disconnect
    bt_rfcomm_disconnect(2);

}

/**
 * main function that initializes the hardware, led, terminal, bluetooth
 * and acl communication stack and registers some predefined commands.
 * Use tab-tab to see the registered commands once the program is running.
 */
int main(void)
{
   // serial baud rate
    u_long baud = 57600;

    // hardware init
    btn_hardware_init();
    btn_led_init(1);

    // init app uart
    NutRegisterDevice(&APP_UART, 0, 0);
    freopen(APP_UART.dev_name, "r+", stdout);
    _ioctl(_fileno(stdout), UART_SETSPEED, &baud);

    // hello world!
    printf_P(PSTR("\n# --------------------------------------------"));
    printf_P(PSTR("\n# Welcome to BTnut (c) 2005 ETH Zurich\n"));
    printf_P(PSTR("# rfcomm-cmd program version: %s\n"), PROGRAM_VERSION);
    printf_P(PSTR("# --------------------------------------------"));
    printf_P(PSTR("\nbooting bluetooth module... "));

    // bluetooth module on (takes a while)
    btn_hardware_bt_on();

    // Start the stack and let the initialization begin
    stack = bt_hci_init(&BT_UART);
    bt_hci_write_local_cod(stack, BT_HCI_SYNC, 200);
    printf_P(PSTR("ok.\n\r"));

    // give hint
    printf_P(PSTR("hit tab twice for a list of commands\n\r"));

    // terminal init
    btn_terminal_init(stdout, "[rfcomm-cmd]$");
    bt_cmds_init(stack);

    // Start L2CAP and RFCOMM
    l2cap_stack = bt_l2cap_init(stack, 8, 8, BT_L2CAP_HCI_PACKET_TYPE);
    l2cap_cmds_init(l2cap_stack, 1, BT_L2CAP_MIN_MTU, BT_L2CAP_MTU_DEFAULT);

    rfcomm_stack = bt_rfcomm_init(l2cap_stack, BT_RFCOMM_DEF_MFS, 4, 5);
    rfcomm_cmds_init();

    bt_cmds_register_cmds();
    btn_cmds_register_cmds();
    nut_cmds_register_cmds();
    l2cap_cmds_register_cmds();
    rfcomm_cmds_register_cmds();

    btn_terminal_register_cmd("sendsms", send_sms);

    // terminal mode
    btn_terminal_run(BTN_TERMINAL_NOFORK, 0);
    return 0;
}
```

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