TECHNICAL UNIVERSITY OF CRETE
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Custom Over The Air Programmable Embedded Radios

by

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Abstract

This thesis develops hardware, middleware and software towards a custom and low-cost remotely programmable radio network testbed. Such testbed is envisioned as a tool for the telecom researcher to develop, deploy and debug radio network projects and applications. To the best of the author's knowledge, this is the first attempt towards a radio network testbed, designed and built in a Greek university from first principles. Key features of the testbed include: simplicity of use, reliability and remote programmability. Furthermore, each carefully designed wireless transceiver node enables environmental sensing and personal computer interfacing at a relatively low cost (30Euro bill of materials for each transceiver assuming relatively small quantities), due to in-house design and fabrication. The proposed testbed consists of various software and hardware components designed to facilitate experimental work for the telecom engineer/researcher. Functional demonstrations are presented, including remotely programmable relay networks as well as medium access control networks.

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List Of Abbreviations

MCU	MicroController Unit
ADC	Analog to Digital Converter
WSN	Wireless Sensor Network
IC	Integrated Circuit
CPU	Central Processing Unit
OTAP	Over The Air Programming
RSSI	Received Signal Strength Indication
OS	Operating System
RTOS	Real Time Operating System
KB	Kilo Byte (1024 Bytes)
FSK	Frequency Shift Keying
MSK	Minimum Shift Keying
SMD	Sourface Mount Device
SMT	Surface Mount Type
SMA	SubMiniature version A connector
PCB	Printed Circuit Board
CAD	Computer Aided Design
AGC	Automatic Gain Control
CRC	Cyclic Redundancy Check
RDT	Reliable Data Transmission
LBT	Listen Before Talk
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
IDE	Integrated Development Environment
Hex	Hexadecimal
FSM	Finite State Machine
EOT	End Of Transmission
EOF	End Of File
LED	Light Emitting Diode
ISR	Interrupt Service Routine
UHF	Ultra High Frequency
DIP	Dual In-line Package

Chapter 1

Introduction

1.1 Wireless Sensor Networks, a brief review

Nowadays the need for telecommunications at all levels has become critical for all modern societies. To meet such need, new discoveries in all scientific fields have been made, leveraging telecommunications at totally new levels. One of the greatest achievements in the telecom field are the design of wireless sensor networks (WSNs).

A WSN is a network consisting of a number of small units that can communicate with each other and can sense environmental variables such as temperature, luminosity, humidity e.t.c. Each such unit is called a node and it consists of several parts.

To start with, every node requires a processing unit. For this purpose, a micro controller unit (MCU) is utilized. More specifically, MCUs are devices that can perform calculations, analog to digital conversions and interface with each node's peripherals. The characteristics that separate MCUs from other processing units (e.g x86 CPUs) are the low power operation, the small form factor and the extremely low cost (starting even from 2 cents).

Furthermore every WSN node utilizes a wireless radio communication module. This module is controlled by the MCU in order for the node to act as a transceiver of data from and to other nodes. Similarly to the MCU, the radio module is of low cost, small and demands low power. It can be easily seen that multiple nodes like the one described above can form a network.

Moreover, another important part of the WSN node is its power source, which is usually a battery and/or an energy harvesting device (for example a solar panel). Finally WSNs being sensor networks, make use of sensors in order to extract data from the environment.

1.2 Prior art in the field

Wireless sensor networks is a technology that is under development for more than 15 years. Therefore, a large number of implementations have been presented so far. Cited bellow is a list[1] with a number of popular WSN nodes:

1. Crossbow TelosB [17]
2. Crossbow Micaz/Mica2 [19]
3. Memsic IRIS [5]
4. Memsic LOTUS [4]
5. ETH University BTnode [18]
6. Coalesenses iSense [3]
7. Libelium Waspmote [2]

Our work in [21] provides a comparative study between the node described in this thesis and commercial Micaz, Isense and BTnode. The comparison regards features such as the battery life, wireless and wired connectivity capabilities, programming environment, etc. According to the study, the node developed (namely iCubes[2]) competes with other WSN nodes, either commercial or academic. A more extensive comparison between all referenced node implementations is beyond the scope of this thesis.

Nevertheless, it could be noted that the wireless sensor network developed is mainly focused in telecommunication research and education. More specifically, software and hardware developed were engineered in order to be easily used by a telecommunication engineer not specialized in embedded systems. For this reason, all firmware was written in plain C and usage of complex real time operating systems (RTOS) such as tinyOS [13] was avoided. Moreover, an MCU with a finely written manual was selected in order to facilitate

[1] A more comprehensive list of available wireless sensor nodes is cited in [6]

[2] The term "iCube" has been also used for an R&D Group [**?**] and a visualization studio [**?**]

micro-controller familiarization, which at most cases is a crucial factor of development delay. Finally, the remote programmability that was developed, does not require the use of a RTOS. This is a powerful feature of this work.

On the other hand, the nodes listed above focus mainly in sensing applications developed by embedded system engineers. For this reason, supported functions such as remote programmability, are unavailable without the use of a RTOS. This property is not desired by an engineer who is not familiar with firmware development using the principals of embedded operating systems and embedded systems in general. Moreover, operating systems such as tinyOS require complex installation procedures which add an extra delay to the total development time of a project. Finally, the manuals of MSP430 and ATmega MCUs, utilized by most of the popular WSN nodes are not that easily readable compared to the manual of the C8051F320 MCU, utilized in the iCubes node (this work).

Chapter 2

Hardware

2.1 Node specifications

The node was developed as a project of the Analysis and Design(Synthesis) of Telecom Modules course during the 2009 spring semester [20]. Below is a brief description of the node specifications.

2.1.1 MCU

The microcontroller unit is the C8051F320 [11] from Silicon Laboratories [1]. It incorporates an 8051 core, a 10-bit Analog to Digital Converter (ADC), two comparators, 2304 KB of RAM and 16KB of flash memory. The main reason this MCU was selected is the finely written manual. This facilitates the development of research programs as well as complex applications. Moreover, the 8051 instruction set is widely known, therefore making application development easier. Finally C8051F320 is designed for low power operation without compromising variety of peripherals, flexibility and battery life.

2.1.2 Radio module

The radio module is the Chipcon/TI CC2500 [12] transceiver. Its frequency of operation is at the 2.4 GHz band with maximum transmit power of 1 dBm and programmable rate up to 0.5 Mbps. It was selected due to its wide range of tunable parameters regarding digital communication that can be easily set by modifying specific control registers.

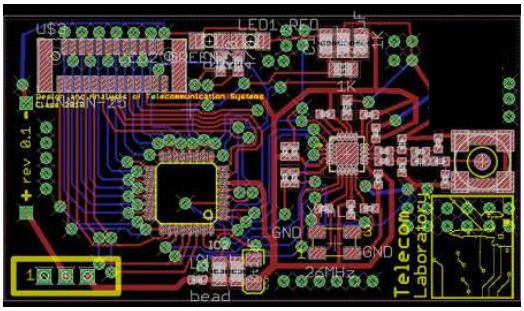
Listed below are some of the radio parameters that can be adjusted:

- carrier frequency and frequency channel (parameterized for frequency hopping applications),
- transmission power,
- type of FSK modulation and respective frequency deviation (continuous phase FSK i.e. MSK, is also supported),
- OOK modulation,
- variable rate and receiver filter bandwidth,
- number of preamble bits used for bit-level synchronization,
- number of bytes used for byte-level synchronization (sync word),
- receive signal strength indication (RSSI) activation and automatic gain control (AGC),
- cyclic redundancy check (CRC).

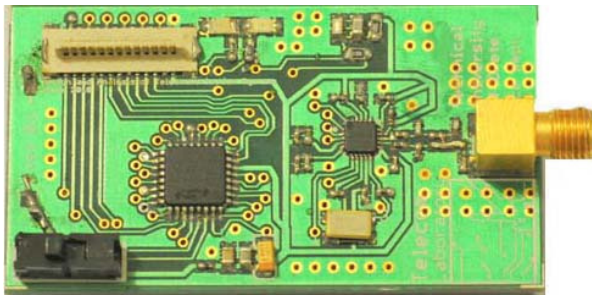
2.1.3 Printed Circuit Board Design

The node was initially designed using two different development kits, a Chipcon/TI CC2500EMK radio evaluation module, and a C8051F320DK MCU development kit. The two development kits were interconnected using simple wiring. Therefore, the first update of the node was the design of a custom PCB. This way, the CC2500 radio IC and the C8051F320 MCU would be placed on the same board and the whole node would have a smaller form factor.

For the purpose of this design, Eagle [14], a free-license computer aided design (CAD) software tool from Cadsoft was utilized. The design was based on the previously mentioned development kits and the pins of the MCU were routed to a pin header in order for extension boards to be accommodated. Finally, special attention was given to the minimization of the electromagnetic interference (EMI). The PCB (design and prototype) is depicted in Fig. 2.1.



(a) Printed circuit board (PCB) prototype.



(b) Printed circuit board (PCB) prototype with installed components.

Figure 2.1: Printed circuit board (PCB) design and prototype of iCubes v0.2.

2.2 Extension Board (XTboard)

2.2.1 Description

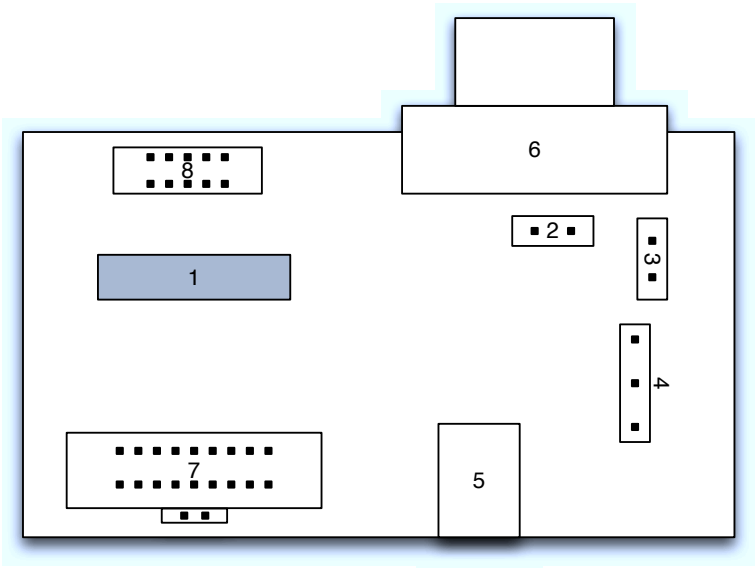
Once full functionality of the node was verified and debugged, there was urgent need for several extensions and connectivity capabilities. Such extensions were:

- Programmability using the Silabs USB debug adapter.
- Power supply using the Silabs USB debug adapter.
- Power supply using an external power source (e.g. C8051F320DK 9V power supply).
- PC connectivity with an RS232 port.
- MCU pinout interface using standard low-cost 2 mm DIP headers.

The board was designed to meet the above needs. The architecture of the design was based on the C8051F320 development kit. For this reason, the hardware components below were utilized:

- National Semiconductors LM2937-3.3 for the voltage regulation from the Silabs USB debug adapter 5V power, as well as the 9V DK power supply [15].
- Sipex SP3223EY, a +3.0V to +5.5V RS-232 transceiver for the RS-232 connectivity [16].

In addition, for the connectivity of the RS232 interface, the power source and the programming interface, an RS232 D-Sub connector, a power jack (barrel type) and 2 mm headers were also utilized in the design respectively. Finally, for the connection between the node and the extension board, a 25 pin SMT male connector was used. The design scheme of the XTboard is presented in Fig. 2.2.



1. 25 pin SMT Connector (Bottom Layer).
2. P0.4 MCU PIN and UART TX pins.
3. P0.5 MCU PIN and UART RX pins.
4. Power Supply Selection (USB or Power Connector).
5. Power connector (5 to 15 VDC unregulated power adapter).
6. DB-9 connector for UART0 RS232 interface.
7. C8051F320 Pinouts.
8. DEBUG connector for Debug Adapter interface.

Figure 2.2: XTboard Layout

2.2.2 Design Constraints

Apart from the above specifications, the board was designed in order to meet certain dimension constraints. Specifically, the limits of the interface board's dimensions were set by the node's switch, bottom side, SMA and positioning of the SMT 25 pin connector. For an explanatory image, see Fig. 2.3.

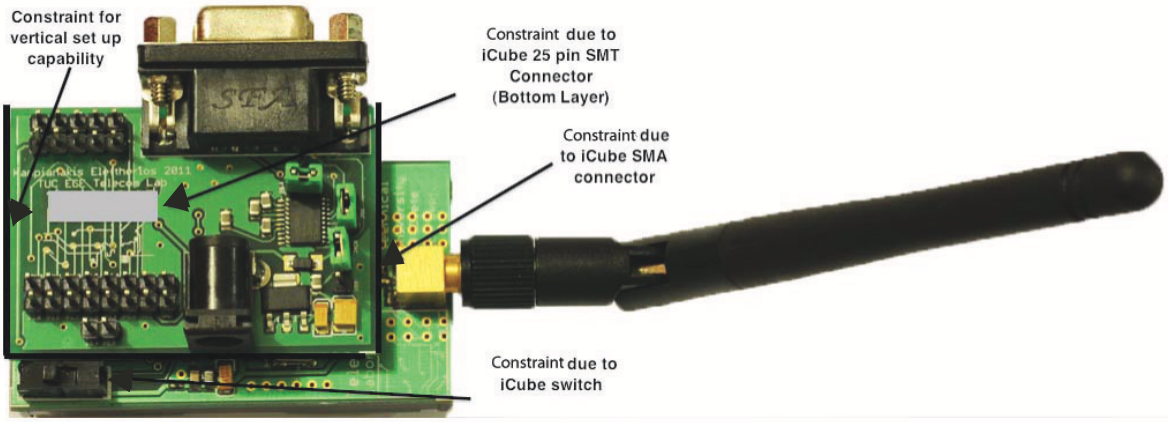


Figure 2.3: XTboard constraints figure.

As seen in the picture, the XTboard had to be carefully designed, according to the following constraints:

- The RS232 should be accessible when the iCube was set up in the vertical position. That means that the RS232 connector could not be placed at the left side of the PCB (Fig. 2.3).
- The length of the PCB should not exceed the limits set by the end of the iCube on the left side (as seen in Fig. 2.3) and the SMA connector on the right side.
- The 25 pin SMT connector should be placed in a position convenient for the design and accessible by the iCube.

Such constraints were simultaneously met with the design of Fig. 2.2 The final outcome of the developed XTboard is depicted in Fig. 2.4.

(a) XTboard printed circuit board (PCB) prototype.

Figure 2.4: XTboard on iCubes node in vertical position.

2.2.3 How to use the XTboard

Below is a set of instructions, to make use of the capabilities offered by the extension board. For a visualization of the XTboard components see Fig. 2.2.

- RS232 connectivity:
  - Use a jumper to short-circuit the P0.4 MCU pin and the RX SP322 pin.
  - Use a jumper to short-circuit the P0.5 MCU pin and the TX SP322 pin.
  - Connect the RS232 adapter to a PC and to the interface board.
- Power node using the 9V power supply:
  - Use a jumper to short-circuit the input to the voltage regulator and the power jack barrel connector output.
  - Plug in the 9V power source into the connector.
- Power node using the Silabs USB debug adapter:
  - Use a jumper to short-circuit the input to the voltage regulator and usb power source.
  - Plug in the debug adapter to the corresponding connector. A sign is drawn on the PCB for the correct connection side.
  - Connect to the device using the Silabs or Keil IDE.
- Programming interface using Silabs USB debug adapter:
  - Plug in the debug adapter to the corresponding connector. There is a sign drawn on the PCB for the correct connection side.
  - Connect to the device using the Silabs or Keil IDE to download code.

However, there are some particularities that the user has to look after. Specifically:

- The power supply current should not exceed 15Volts.
- Only one power source between batteries and USB or SiLabs power adapter must be used at a time. In the opposite case, current will flow from the voltage regulator to the batteries.
- If The SiLabs USB Debug Adapter in not connected according to the shape drawn on the PCB, the MCU is at risk of being burned.
- To avoid dangerous current spikes, the node must be turned of during the connection of any peripheral.

Chapter 3

Point to Point Communication and CSMA/CA Middleware

A critical element in the development of a WSN testbed is the communication between nodes, in terms of reliable data transfer, medium access control and low power transmission/reception of data. To accommodate this, a set of primitive software functions was developed.

3.1 Reliable Data Transfer

3.1.1 Protocol Description

One of the basic principles of a successful Over The Air Programmability (OTAP) is the establishment of a reliable connection between the master programming gateway and the slave node. Thus, such a connection was designed for the purposes of the OTAP and of course for general purposes. The algorithm for a Reliable Data Transfer link (RDT), was taken from the work done in [22]. To begin with, in order to model the real wireless channel, the following assumptions are made :

- The channel may flip bits in the transmitted packet (either data or acknowledgement).
- A packet can be lost during transmission.

The purpose of the RDT algorithm is to transfer a packet as reliably as possible through an unreliable channel. To begin with, the transmitter after sending a packet shall have knowledge of the packet's good reception.

For this reason the receiver sends back a special packet, also known as acknowledgement (ACK). The transmitter waits for the ACK for a specified time called *Timeout*. Listed below are the reasons why an ACK may not be received by the transmitter :

1. The data packet was not received from the receiver, therefore the node did not send an ACK.
2. The data packet had flipped bits and the error detection algorithm rejected the packet on the receiver, and the node did not send an ACK.
3. The ACK arrived to the transmitter after the timeout expired.
4. The ACK was not received at the transmitter.
5. The ACK had flipped bits and the error detection algorithm rejected the packet on the transmitter.

Each packet includes:

- The payload data (if it is a data packet).
- The packet sequence bit.
- A field that states if the packet is data or ACK.
- The source MAC address.
- The destination MAC address.

The packet size is tunable with the use of definitions placed in the RDT.h file, namely RXBUFFER_SIZE and TXBUFFER_SIZE.[1].Fig. 3.1 presents the packet structure of the RDT algorithm.

[1]Two separate buffers are needed for packet reception and transmission respectively.

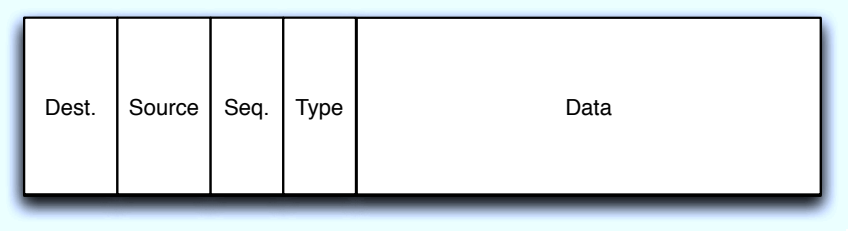


Figure 3.1: Packet structure.

In the emplemented RDT algorithm, if any of the above events occurs, the transmitter resends the data packet and waits for ACK reception. There is a limit regarding the number of times that the transmitter will resend a data packet. This limit is defined in the RDT.h library of the code as MAX_TRIES. When the number of retransmissions without receiving the correspondingACKs exceeds this limit, the routine returns that the reliable packet transmission was unsuccessful.

Furthermore, as seen above, each packet includes a sequence bit. The sequence bit is kept in a variable both at the transmitter and the receiver node. Once the transmitter sends a data packet and receives the corresponding ACK, it flips the sequence bit. Moreover, the receiver, after the transmission of an acknowledgement also flips the sequence bit. This way, the packet sequence between transmitter and receiver is retained. The preservation of the packet sequence is a way of handling the scenario of lost acknowledgements. Once an ACK is lost, the ACK timeout timer of the data transmitter expires and a data retransmission occurs. In this case, the receiver will receive a duplicate data packet. However, by utilizing a check on the sequence number of the packet, the receiver will recognize the duplicate packet, send an ACK with the same sequence number of the duplicate data packet and ignore the latter. Thus, the transmitter will receive an ACK for the corresponding data packet and the receiver will ignore the duplicate data packet, since the RDT packet reception routine will return “false”. Fig. 3.2 and Fig. 3.3 depict the functionality of the RDT transmitter and receiver respectively.

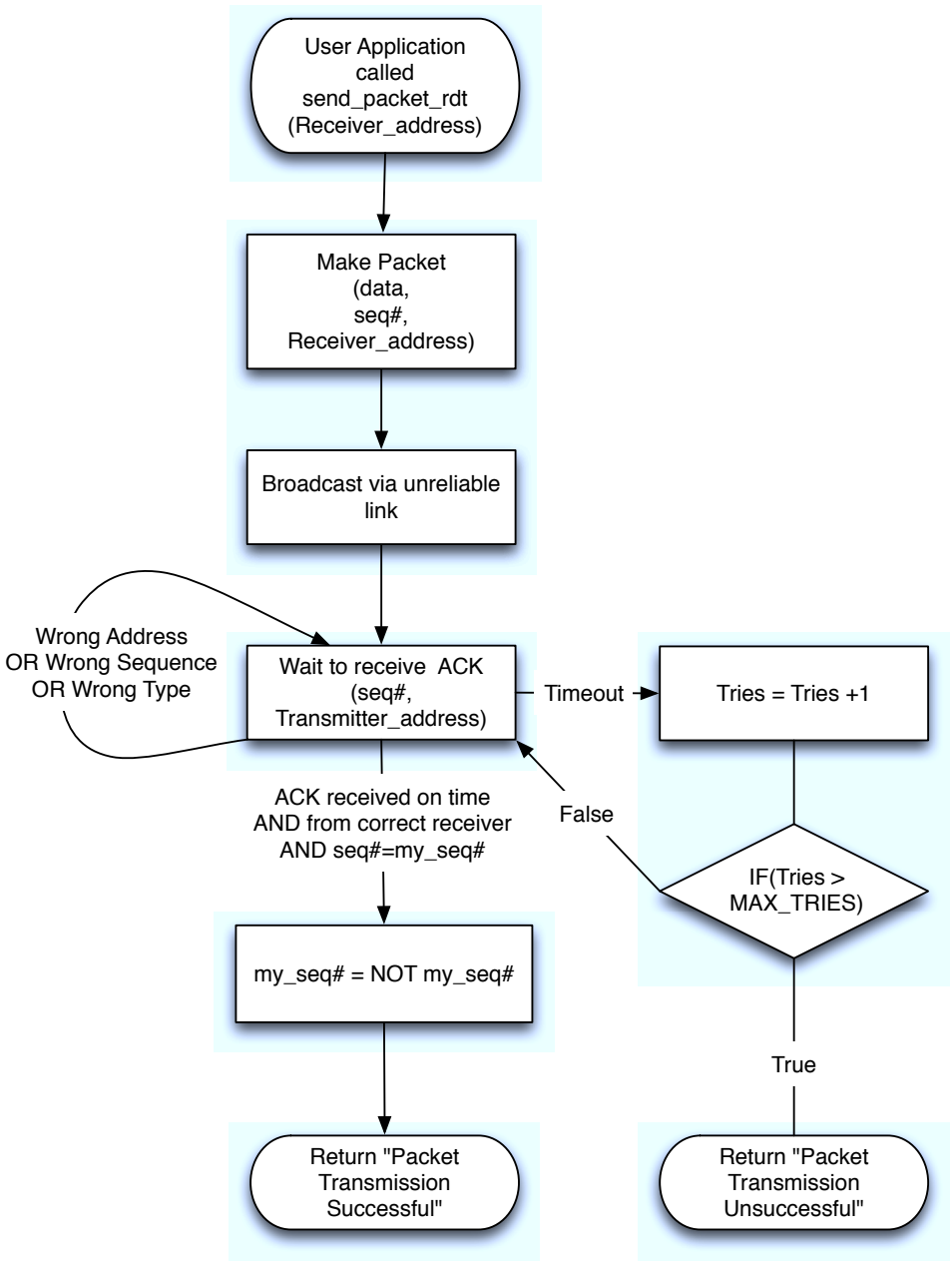


Figure 3.2: RDT Transmitter Finite State Maschine (FSM).

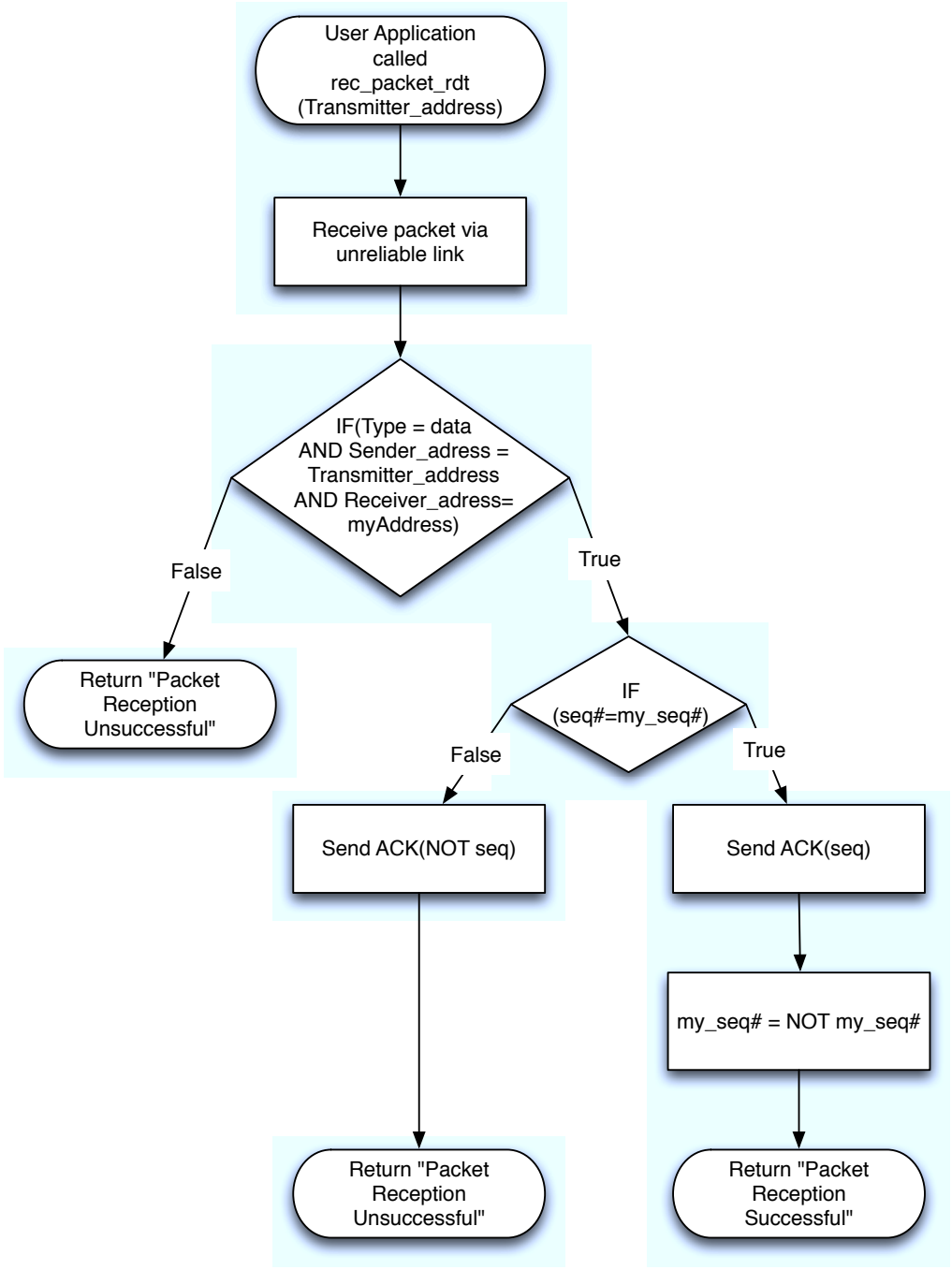


Figure 3.3: RDT Receiver Finite State Maschine (FSM).

3.1.2 How to use Reliable Data Transfer

There are basically two routines developed for reliable data transfer; one for packet reception and one for packet transmission:

- receive_packet_rdt (BYTE from mac_address)
- transmit_packet_rdt(BYTE to mac_address)

The function prototypes are self explanatory. In order for the implemented RDT protocol to be functional, the nodes that utilize it have to claim a special network address. The address definition is stored in the RDT.h library under the name MAC_ADDRESS. This definition is sent with every packet (data or ACK) in the source address field which is one byte long.[2] Therefore, packets can be sent at a receiver of choice and the receiver can filter out packets from multiple transmitters. An abstract example of the RDT routines developed is given below:

```
1  //Receiver code
2  main(){
3      if(receive_packet_rdt(TX)){
4        //If a correct packet is received blink LED1
5        LED1 = !LED1;
6
7        //Here rxBuffer has the last data sent
8      }else{
9        //else blink LED2
10       LED2 = !LED2;
11     }
12   }
13 }
```

[2]With the current settings, the maximum number of addressable nodes is 255.

```
1  //Transmitter code
2  main(){
3      if(send_packet_rdt(RX)){
4        //If a packet is transmitter successfully blink LED1
5        LED1 = !LED1;
6      }else{
7        //else blink LED2
8        LED2 = !LED2;
9      }
10   }
11 }
```

The above code, if downloaded to both the test transmitter and receiver would establish a reliable link between two nodes.

3.2 Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA)

3.2.1 Protocol Description

One of the fundamental communication protocols for the link layer in wireless networks is the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). The protocol described is a multiple access method that allows several nodes which use the same transmission frequency channel to transmit and share its capacity. For the developed CSMA/CA algorithm, the following functionality is utilized:

At the transmitter side, the node listens for currently transmitted data over the air. If data is being transmitted, the node enters sleep mode for a random time interval. If the channel is clear, the node transmits the data, initiates a timer to measure a timeout and waits for an ACK. If the timer expires, the node enters sleep mode for a random time and resets the procedure. At the receiver side, the node is in receive mode and once a packet is received, it listens to the channel for carrier power and once it is clear, it sends back an ACK. The FSMs of the transmitter and receiver are depicted

in Fig. 3.4 and Fig. 3.5, respectively. The type of protocols that try to transmit when no packets are being transmitted simultaneously are called Listen Before Talk (LBT).

Before the implementation of the CSMA/CA, algorithm took place, two special functions had to be implemented: Carrier Sense function and Sleep function. Their description follows:

Carrier Sense

As stated above, CSMA/CA is a Listen Before Talk (LBT) protocol. LBT functionality is performed by using a carrier sensing capability, provided by the CC2500 radio module. Carrier sensing is performed by setting up the CC2500 radio to measure the received signal strength at a selected frequency. For the purpose of the CSMA algorithm implementation, a special function was designed. The function, namely "channel_clear" has a boolean type return value, used to indicate whether the channel is clear or not. For this implementation, a timer is used, initialized once the function is called. If a carrier with a detected RSSI level above a predefined threshold is detected before the timer expires, the function returns FALSE, indicating a non clear channel.

Low Power Sleep

Additionally, another property of the CSMA is the random duration, low power sleep. For the purposes of low power sleeping, a special function was developed. When it is called, all MCU peripheral states and the system clock are saved in temporary functions. Followingly, all peripherals are shut down, the system clock is configured to oscillate at its lowest frequency and the MCU enters *idle* mode. Moreover, a timer is configured to expire based on the time argument inserted in the sleep function. After the timer expires the peripheral and the system clock states are set to their previous ones and the MCU enters active mode. During sleep mode, the MCU consumes around 0.32 mA, when compared to the 11.5mA in active mode @ 24Mhz clock, is three orders of magnitude lower.

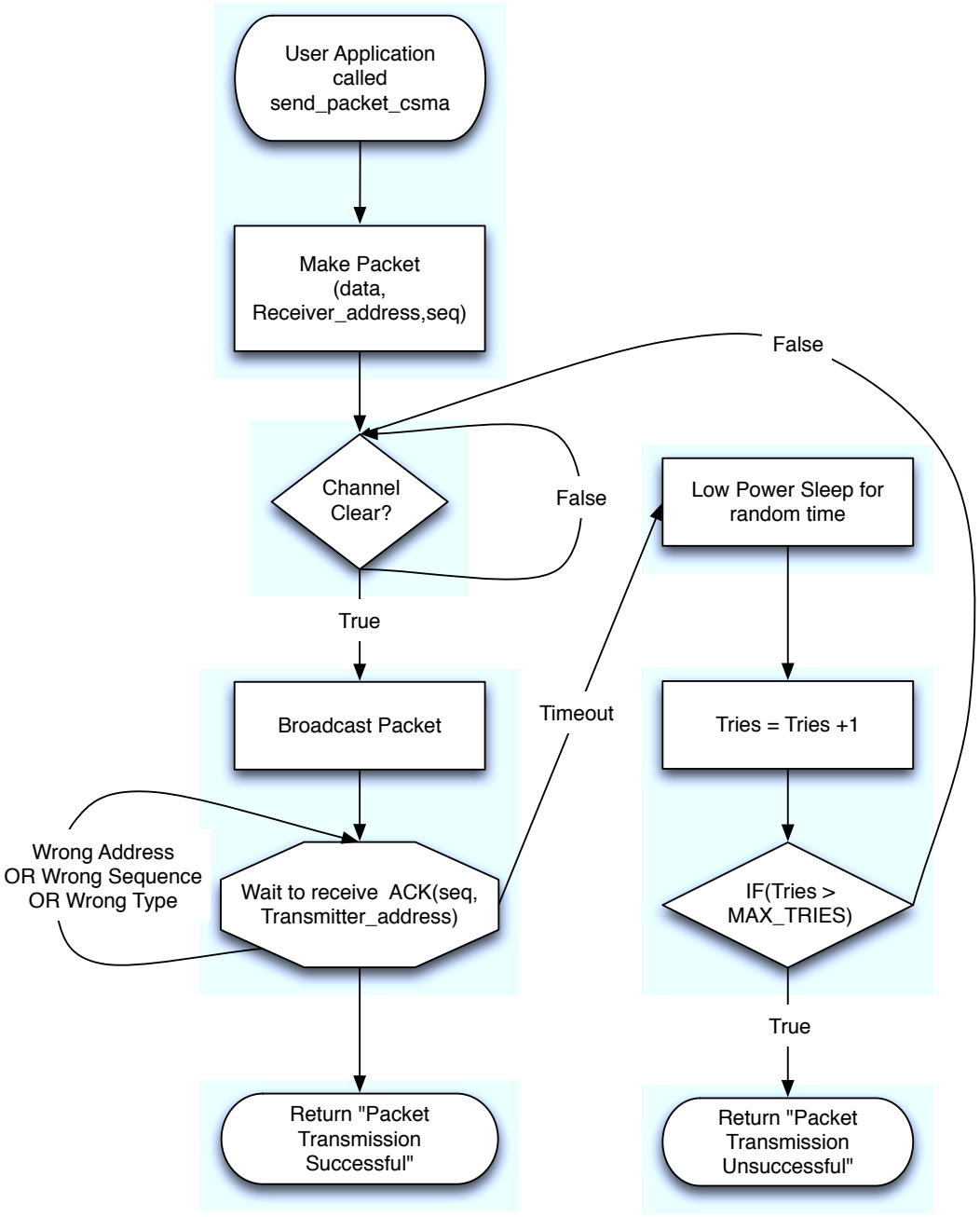


Figure 3.4: CSMA Transmitter FSM.

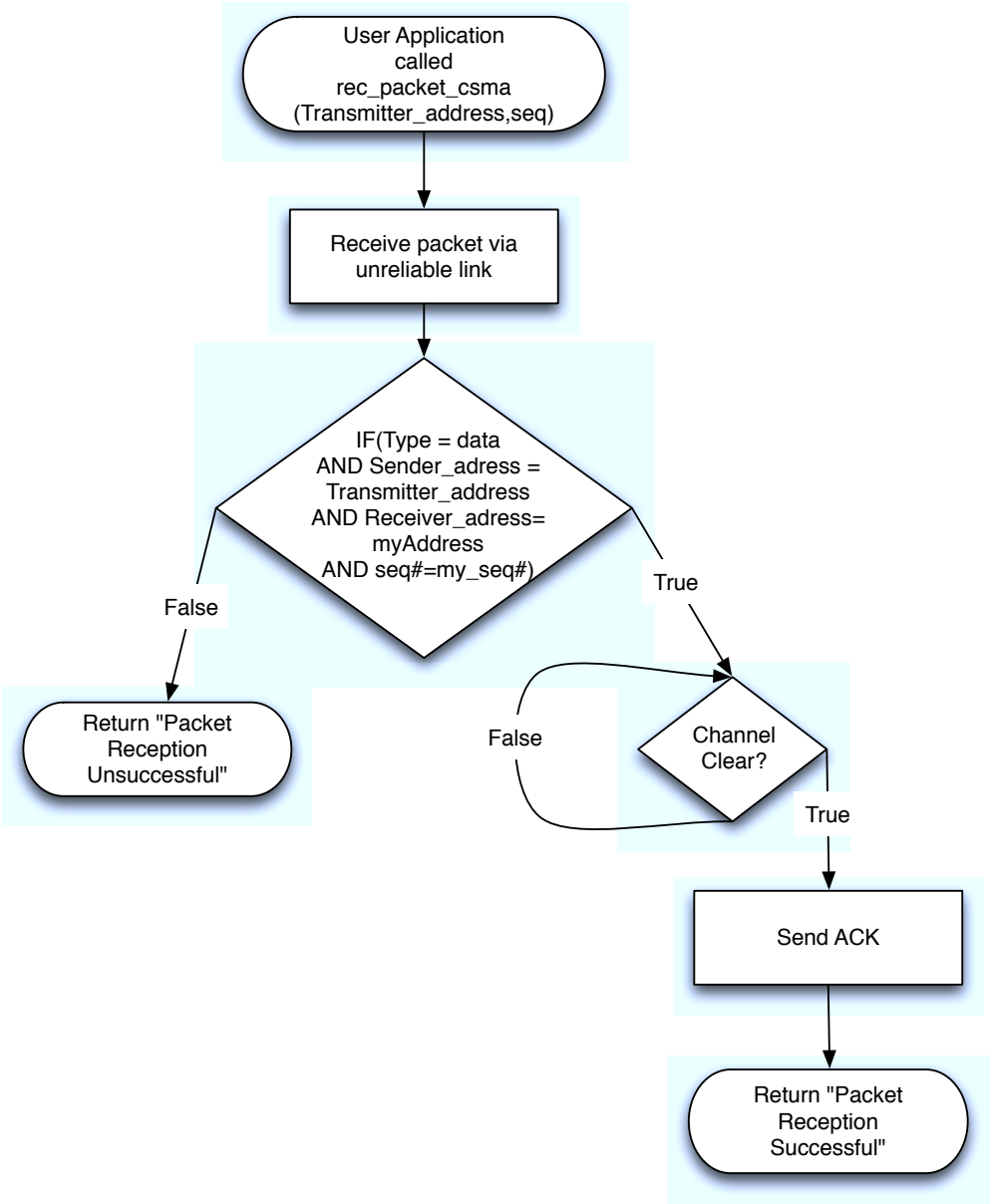


Figure 3.5: CSMA Receiver FSM.

3.2.2 How to use CSMA/CA

As with the RDT implementation, there are two different routines that are utilized in order for packets to be transmitted or received. These are:

- transmit_packet_csma (BYTE receiver_address)
- receive_packet(BYTE transmitter_address)

Arguments in the functions are also the sequence number, the ACK timeout and the carrier sensing timer timeout. An example code for the usage of the CSMA/CA algorithm developed follows :

```
1  //Receiver code
2  main(){
3    if(MAC_ADDRESS == RX){
4      if(receive_packet_csma(ACCEPT_FROM_ALL)){
5        //If a correct packet is received blink LED2
6        LED2 = !LED2;
7        //Here rxBuffer has the last data sent
8      }
9    }
10 }
```

```
1  //First transmitter code
2  main(){
3    if(MAC_ADDRESS == TX1){
4      if(send_packet_csma(RX)){
5        //If a packet is transmitter successfully blink LED1
6        LED2 = !LED2;
7      }
8    }
9  }
```

```
1 //Second transmitter code
2 main(){
3   if(MAC_ADDRESS == TX2){
4     if(send_packet_csma(RX)){
5       //If a packet is transmitter successfully blink LED1
6       LED2 = !LED2;
7     }
8   }
9 }
```

The abstract code above depicts the functionality of the functions developed. The receiver node calls receive_packet_csma with an input argument ACCEPT_FROM_ALL. This definition is used in the implementation of the receive packet function, in order to disable the transmitter filter. The nodes with addresses TX1 and TX2 enter send_packet_csma() using as input argument the receiver's mac_address. This way, multiple transmitters try to access the same channel and once collision is detected, sleeping for random time is initiated.

Chapter 4

Over The Air Programmability Middleware

The major objective of this diploma thesis is the remote programmability of the WSN. The normal procedure for programming one of the nodes require physical contact with the node to be programmed.

Particularly, that means that the user needs to either move the node from its position in the network and place it close to a computer to program the node, or get the computer to a position close to the node where the programming interface can be physically attached. The need for physical contact between the programming interface and the node introduces crucial application constrains. For example, if the node has to be set up on a location with difficult or no human access, the node could be only programmed once, resulting to non-updatable, error prone operation.

Moreover, the procedure for programming a wireless sensor network with methods and devices that require physical contact is time consuming and messy. As an example, the time required to program an iCube node using the SiLabs debug adapter and the XTboard is about 15 to 17 seconds.[1] Additionally, the movement of wiring and nodes and the repeated connection and removal of the programming adapter can be a messy or even dangerous procedure for node integrity. Fig. 4.2 depicts the 4 connections required in order to program 4 iCube nodes.

The solution to this critical problem was introducing the capability wireless network programming, or in other words Over The Air Programmed (OTAP). OTAP is a method of distributing firmware to a sensor network wirelessly, thus avoiding physical contact with network nodes. With the

[1] Personal experiences, timings may vary.

OTAP utilization, a WSN can be programmed regardless of it's physical position, and without the requirement of any movement, not even from the engineer. Moreover, OTAP is a feature that greatly accelerates the project developing process. That is because the average time for wireless programming per node is about 2 to 3 seconds, thus decreasing the programming even for one order of magnitude. Fig 4.1 shows the setup of the wirelessly programmed network. It can easily be seen that this is a "cleaner" and easier to setup programming procedure.

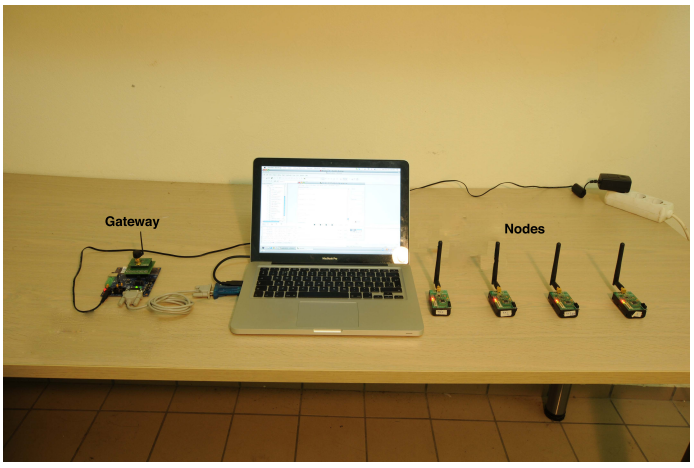


Figure 4.1: Programming 4 nodes with OTAP.

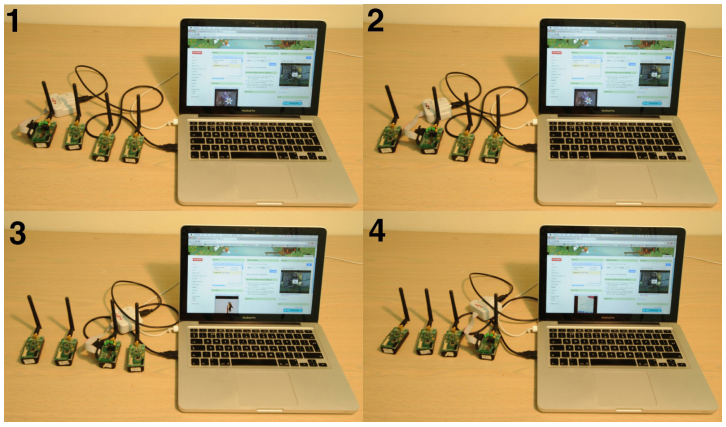


Figure 4.2: Programming 4 nodes with debug adapter.

4.1 Important OTAP Definitions

Before introducing the main components required for the OTAP, some important definitions are quoted in order for the reader to be able to understand all the aspects of this important procedure.

4.1.1 In system programmable Flash memory

The C8051F320 chip, utilizes a 16KBytes flash memory. The purpose of this memory is to store both non-volatile data and the program code. The flash memory can be written through the debug interface or by middleware with functions in the FlashPrimitives.h C library. Specifically, the user, with the appropriate use of the Flash Primitives functions can write middleware that can alter the code stored in the Flash memory (code space) and execute it. A simple pseudocode example of writing and executing code in-application is depicted below:

```
1  //A random 8051 instruction bytecode
2  Instruction the_instruction = 0x12345678;
3
4  //The instruction's address in flash
5  long instructionAddress = 0x1200;
6
7  //Write the instruction to flash memory
8  write_instruction_to_flash(the_instruction,instruction_address);
9
10 //Execute instruction
11 jump instruction_address;
```

In the above abstract code, a byte array is declared, that an instruction is represented in bytes. Then, the instruction is written in the flash memory and executed using a *jump* command.

4.1.2 Compilation and download process

The procedure with which a C program is downloaded in the code space of the MCU memory and specifically the C8051F320, using the Keil PK51 [**?**] tool chain, is the following:

1. Preprocessing - The preprocessor handles the logic behind all the dash (#) beginning directives of the program (Cx51 Compiler).

2. Parsing - A parse tree is created, a structure necessary for the translation step (Cx51 Compiler).

3. Translation - Assembly code object files are produced (Ax51 Assembler).

4. Linking - The object files produced by the assembler are linked together in a single object executable file (BLx51 Linker).

5. Hex File Generation - At this point a Hex file generator produces the Hex code that will be downloaded to the device. Consult section 4.1.3 for more info.

6. Download - The final object - executable file is downloaded to the MCU using the Silabs USB debug interface.

The step that needs to be done wirelessly in order for the OTAP to be successful is the final one, the Download.

4.1.3 Intel Hex Code File

Hex code file is an ASCII file that is written in Intel Hex format. Intel Hex format is a file format for transferring binary data information from and to memories. The file contains hexadecimal values that encode a sequence of data and their starting address offset. There are several subtypes of formats, depending on the MCU architecture. The mentioned format applies to 8 bit MCUs. An example follows :

1. $\overbrace{:}^{start}\ \overbrace{0C}^{\#ofbytes}\ \overbrace{28ED}^{address}\ \overbrace{00}^{type}\ \overbrace{ECF0A3EDF0A3EEF0A3EFF022}^{data}\ \overbrace{5E}^{checksum}$
2. :0C28F900ECF208EDF208EEF208EFF2221B
3. :0A2F43003098FDAF99C2987E00227D
4. :00000001FF

Every line is separated in the following parts:

- Character ":" : start of line
- Characters 1 to 2 : number of bytes of data in the line.
- Characters 3 to 6 : the address for the line of data.
- Characters 7 to 8 : the record type (00 means data, 01 means EOF, other types are not supported by 8 bit format).
- Characters 9 to last − 2 : data bytes to be written in flash.
- Last two characters are the checksum for every line.

Provided the above info, the first line of the example is decoded as follows:

- ":" : start of line.
- 0C : the line has 12 bytes of data.
- 28ED : the data bytes are to be written in address 0x28ED.
- 00 : file not ended yet.
- ECF0A3EDF0A3EEF0A3EFF022 : data bytes to be written in the above address.
- 5E : Line checksum.

The above data could be sensor data from a data logging application or the instructions in the MCU's code space. Either way, they are fully described by the format.

4.1.4 STARTUP.A51 file

The STARTUP.A51 is an assembly language file built by Keil, the Cx51 compiler manufactor, that provides the basis of a program start up routine. Specifically the STARTUP.A51 file:

1. Clears DATA, PDATA and XDATA memory.[2]
2. Sets up the reentrant stacks (if necessary).
3. Initializes C global variables.
4. Sets the Stack Pointer (SP).
5. Jumps to the MAIN C function.

All the above are necessary in order for a program initialization to be successful. These steps are also necessary for an execution transfer between different programs stored in the same code space (bootloader and application).

[2]For more information on 8051 memory types, consult Cx51 manual [**?**]

4.1.5 XXXX.M51 file

The M51 file is a linker output file with information about the linking process of a program. There is useful information contained in the file but basically the information valuable for the OTAP process is the link map of the module. In the link map, the following are quoted: the addresses of *XDATA*, *DATA* data variables and CODE memory of the program's functions, variables and constants. It is useful for checking whether the setup of the application to be downloaded and the bootloader are correct. For more information, consult section "how to use OTAP".

4.1.6 Interrupt vectors

When an interrupt occurs, the MCU saves its execution state and initiates the execution of a code named "interrupt handler". The interrupt handler is mainly a piece of code that is executed whenever an interrupt occurs. The memory address where the handler is saved is called an interrupt vector. In the C8051F320 the interrupts are directed to the beginning of the code space a.k.a code space address 0x000. For further information consult the C8051F320 manual, interrupts section. As an example, if the external interrupt 1 (INT1) occurs, the MCU will begin executing the code saved at address 0x0013. After the interrupt handler finishes execution, the MCU program counter is set to where the program stopped when the interrupt occurred.

4.2 Middleware developed

The OTAP project for the developed node is consisted out of four middleware parts :

- The slave bootloader (installed in the node).
- The slave interrupt pseudo-handler (installed in the node).
- The slave user application (installed in the node, developed by user).
- The master firmware updater (installed in the gateway).

4.2.1 Bootloader

The bootloader is the middleware responsible for most of the work of the OTAP. It is the middleware that receives the code wirelessly, writes it to flash memory, checks its validity and starts the downloaded application. Moreover, one of the most important characteristics of the loader is the ability to be executed under any circumstances and application faults. That is possible through a series of mechanisms that state the bootloader stable and always executable. The program start is located in the code space address 0x100. Described below are all of the important functions and capabilities of the bootloader that make the OTAP possible.

Decode and download

Once started, the loader erases the predefined code space where the user application will be stored. The next step is to wait for code to be received wirelessly by using the receive_code() function. This is the function that receives and decodes the incoming Hex file. Below is a brief piece of code in order for the user to understand how this function works.

```
1  do{
2    //ignore all characters until reaching the record mark field
3    while( c = get_key() != ':' ){;}
4    //get the record length
5    len = get_key();
6    //get the MSB of the starting
7    //address (offset field in HEX record)
8    offset = get_key();
9    //shift the variable in order to save the LSB
10   offset <<= 8;
11   //get the LSB
12   offset |= get_key();
13   // get the record type
14   record_type = get_key();
15
16   //check the record type
17   if( record_type != 0 && record_type != 1 ){
18     //if the record type is not valid
19     return CODE_NOT_VALID;
20   }
21
22   //init a flash pointer with the record's offset
23   flash_pointer = offset;
24
25   //write the data field of the hex file until all data ends
26   for(i = 0 ; i < len ;i++){
27     if(flash_pointer < LAST_FLASH_ADDRESS){
28       FLASH_ByteWrite(flash_pointer++,get_key());
29     }else{
30       //if there is a try to write in a non valid address
31       return CODE_NOT_VALID;
32     }
33   }
34
35   //init a variable to check for checksum validity from flash
36   flash_checksum = 0;
37   flash_pointer = offset;
38   for( i = 0; i < len; i++){
39     // add the data field stored in FLASH to the checksum
```

```
40      flash_checksum += FlashByteRead(flash_pointer++);
41    }
42
43    // get the HEX record checksum field
44    checksum = get_key();
45
46    // add the remaining fields
47    flash_checksum += len;
48
49    // Take the shifted by 8 bits offset variable
50    // and add it to the flash_checksum
51    //This is done, in order to take only
52    //the 8 most significant bits of the variable
53    flash_checksum += (char) (offset >> 8);
54    // Mask the offset field in order to  take the
55    // 8 least significant bits of the offset variable
56    flash_checksum += (char) (offset & 0x00FF);
57    // This is done because flash_checksum variable
58    // is smaller than the offset variable and adding
59    // will lead to an overflow
60    flash_checksum += record_type;
61    flash_checksum += checksum;
62
63    // verify the checksum (the flash_checksum should equal zero)
64    if(flash_checksum != 0){
65      //if checksum is not valid
66      return CODE_NOT_VALID;
67    }
68  }while(record_type != 1);
69
70  //if EOF record type found return that code is valid
71  return CODE_VALID;
```

The above code depicts the main functionality of the receive_code() function. To begin with, using this code, the Hex file is received character by character and thus each line is fully decoded. Moreover, the code received is stored in the addresses described in the "offset" field. Finally, a checksum-type check is executed by reading the contents written in flash thus implementing a test for flash corruption. In any case, if something interrupts the above procedure, the byte stored in flash is already stated as not valid. For example, if a power failure occurs, or a sudden reset for any reason, the bootloader will be the program to be executed and waiting for new code to be downloaded and not the partially downloaded code.

Initialization and application boot

Mentioned above is that once the bootloader is started, a control code is executed in order to verify the validity of the code currently in flash. This code simply reads the validity variable from flash and if it is set, the user application is executed. The execution of the code is done by using C function pointers. A function pointer is a variable that points to the address of a function. By using function pointers, it is possible to initiate a function (or in this case a whole program) only by knowing the address where this function is saved. The example below does exactly that (it is a code block from the bootloader program):

```
1
2   //Declaration of function pointer to application
3   void (*_application_)();
4
5   //Raise the now_running_bootloader flag
6   PSW &= !0x02;
7
8   //Read the validity byte of the code currently in flash
9   valid = FLASH_ByteRead(CODE_VALID_ADDRESS);
10
11  //If code is valid
12  //or the P1_3 attached button is not pressed
13  if(valid == CODE_VALID && P1_3){
14
```

```
15      // assign the function pointer
16      _application_ = (void code*) APP_ADDRESS;
17
18      //raise the now_running_app flag
19      PSW |= 0x02;
20
21      // jump to the application i the flash
22      _application_();
23    }
```

In the case above, a function pointer of a function with void type of return and no arguments is firstly declared. Then, a general purpose bit from one of the microcontroller's registers is set in order for the interrupts to be directed correctly (see "pseudo interrupt vector" section). Finally, if the code is characterized valid, the function pointer is used in order to jump to the application's main(). The code above depicts the described functionality and is executed upon every MCU reset.

Moreover one can observe a more hardcoded check using the MCU's P1_3 port. If this port is short-circuited with the ground pin of the MCU on reset, whatever the validity bit, the execution is transferred to the bootloader program. This functionality gives the user the ability to initiate the bootloader at will, even if the application has stalled infinitely. For a more explanatory scheme, see Fig. 4.3.

The use of function pointers was selected instead of in line assembly because the compiler that was used did not have such capability (or at least in a user friendly way). The Cx51 manual is equipped with further information about function pointers.

Hex file transfer

In order for the code file to be transferred, a fast and reliable data link must be established between the programming gateway and the node with the installed bootloader. This is achieved by several means. To begin, the link between the gateway is made reliable by utilizing RDT protocol (See RDT section for more information), thus every packet is acknowledged and there is no possibility for a packet to be duplicated or unsent.

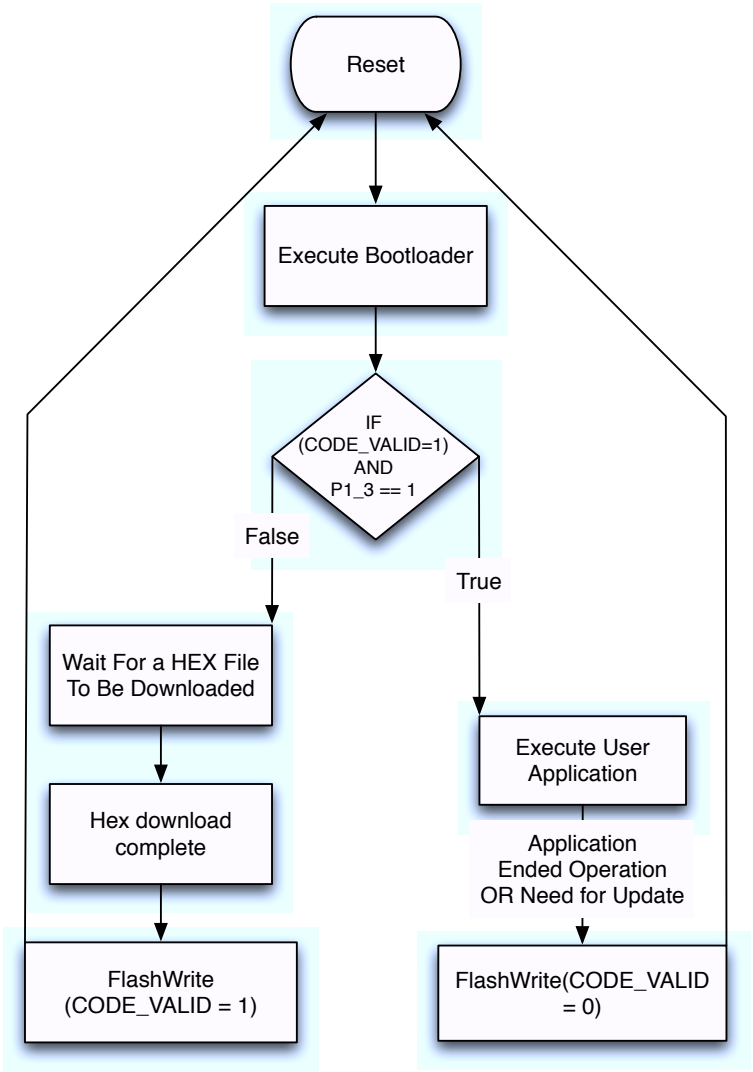


Figure 4.3: Program execution control flow.

Furthermore, with the ability of the CC2500 radio to apply a CRC check on every packet, data reception has but a tiny possibility to be faulty. But then, there is always the checksum of every line, utilized in the receive_code function to cover even that possibility. In addition, every packet contains a variable size buffer of characters that are returned in the correct order by the get_key() function. Below, the aforementioned function is quoted:

```
1  //if the whole buffer has been used by the
2  //receive_code() function
3  if(rxbuffer_counter >= BUFFER_SIZE || init){
4
5    //receive a packet from the gateway
6    receive_packet_rdt(OTAP_GATEWAY);
7
8    //reset the index counter for the receive buffer
9    rxbuffer_counter = INDEX_RX_DATA_START;
10
11   //variable that is set for the first execution of the function
12   //in order for the first packet to be received
13   init = 0;
14 }
15
16 //return the buffer and increment the index counter
17 return rxBuffer[rxbuffer_counter++];
18 }
```

With a quick view on the above code, it is understandable that the program receives packets from the gateway and returns a series of characters until the end of each packet. Then, a new packet is received and the process is reset. This is a standard synchronization method with a buffer that is used for numerous applications.

4.2.2 User application

The user application is the code to be downloaded using the bootloader. The bootloader, as stated above is responsible to jump to this address in order to begin the program execution. The application code has almost no limitations regarding functionality, meaning that every module of the MCU can be used, as if the bootloader does not exist. The two programs are executed completely independently. In order to make the application downloadable, the user must set the application code to begin from an address declared APP_ADDRESS in the "bootloader.h" library (default value 0x1000). In addition, the user has to set up the interrupt vectors to begin at address APP_ADDRESS and set up the STARTUP.A51 file to jump to the address APP_ADDRESS in order for the main function to start (more information in "how to use OTAP" section).

There are certain limitations regarding the memory use of the application. First and foremost, the application, should not overwrite the bootloader code in any way. The address where the loader is saved is stated in the corresponding .M51 file. If a flash write occurs to the bootloader code space, the download operation would be stated error prone and the whole system would be faulty and difficult to debug. Furthermore, the application should not write to a flash address beyond LAST_FLASH_PAGE (default value 0x3BFF) as declared in the bootloader.h library. In this memory bank valuable information is stored, such as the MAC_ADDRESS of the node and the code validity bit. Finally, taking into account the previous limitations, the amount of flash memory available for application code is limited to 11263 Bytes (and not 16KBytes) due to the fact that the application code starts in address 0x1000 and ends at most at 0x3BFF. Of course this is a minor drawback because the typical application memory size varies from 2 to 6 KBytes and at most 10 KBytes of code.

To conclude, a piece of code must be added into the application which, when executed, initiates the bootloader. That way, the OTAP process can be initiated without physical contact with the node. For example, the node could be programmed in such way, that when a special packet is received the

bootloader is started, in order for a new application to be downloaded. The code sequence with which the bootloader is started, within the application code is shown :

```
1 //Write to the  flash memory that the code is not valid
2
3 FLASH_ByteWrite(CODE_VALID_ADDRESS, CODE_NOT_VALID);
4 //Software reset
5 RSTSRC = 0x10;
```

When the above code is executed, the node execution is transferred in OTAP mode and awaits for a program to be downloaded wirelessly. The first instruction unsets the validity of the code. Therefore, upon reset, the bootloader, after checking this variable's value, is initiated (for more info check the bootloader section). This way, the code execution can be transferred from the application to the bootloader and a new program can be downloaded.

4.2.3 Interrupt pseudo-vector

As quoted in the interrupt vector section, when an interrupt occurs, the MCU automatically jumps to the corresponding interrupt vector. In the case of the particular OTAP project, when an interrupt occurs, the execution is transferred to a program that selects whether to direct the interrupt to the bootloader, or to the downloaded user application interrupt service routine. The program is named interrupt pseudo-vector, because it is not actually an interrupt vector but a control program in order for the interrupts to be directed correctly. The selection of which program's ISR will be executed is done by using the "F1" bit from the C8051F320 register "PSW". If this bit is set, the application is the one that is currently running and the interrupt is directed to it, otherwise, it is handled by the bootloader. A code part of the pseudo-vector is depicted below:

```
1  ;DownLoader base address
2  DnlBase Equ   0100H
3  ;Application base address
4  AppBase Equ 1000H
5
6  ;Start Loader
7  CSEG    AT 0
8  Ljmp    DnlBase
9
10 ;INT0 - External Interrupt
11 CSEG    AT 3
12 JB      PSW.1,InterruptV0
13 Ajmp    DnlBase+(3)
14 InterruptV0:
15 Ljmp    AppBase+(3)
16
17 ;T0 - Timer 0 Interrupt
18 CSEG    AT 8*1+3
19 JB      PSW.1,InterruptV1
20 Ajmp    DnlBase+(11)
21 InterruptV1:
22 Ljmp    AppBase+(11)
```

The above assembly code initializes two variables that store the memory addresses of the bootloader and the application. Followingly, it vectors the reset interrupt to the bootloader, in order for the bootloader to run upon every reset and check whether or not to start the application in the code space. Finally, all the other interrupts are vectored according to the PSW.1 bit. If it is set, the program jumps to the application interrupt vectors, while, if not, to the bootloader. With that simple piece of code, the interrupts are vectored correctly independent of which program is currently running. Fig. 4.4 explains this functionality

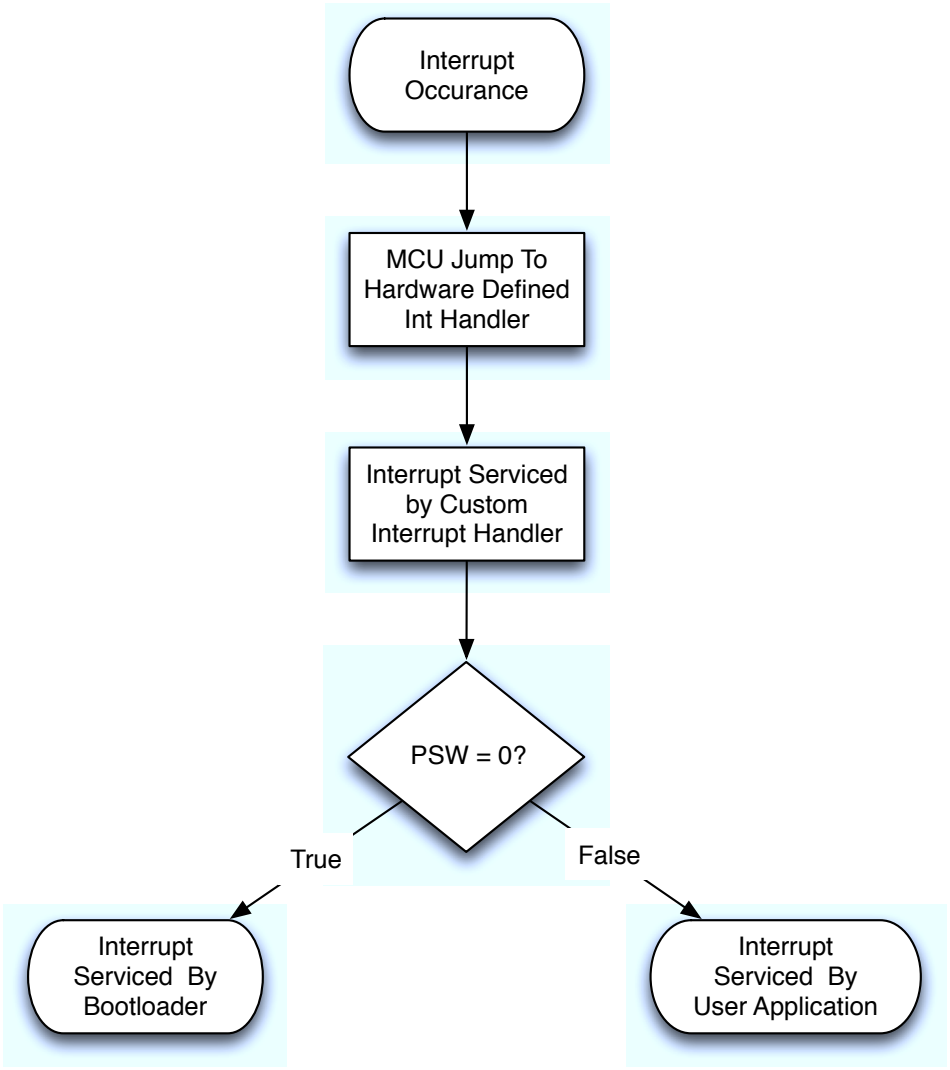


Figure 4.4: Interrupt servicing flow.

4.2.4 Gateway Firmware Updater

The gateway is the device that is responsible for transferring programs wirelessly to the WSN nodes. The developed program flow is fairly simple. To begin, the gateway's flash memory is reset, in order for the previously written program to be erased. Followingly, the user is prompted via the RS232 interface to insert an Intel Hex file. Then the user is prompted to insert the addresses at which the program will be send wirelessly. Finally the inserted Hex file is transmitted to the selected nodes. The gateway program flow is depicted in Fig 4.5.

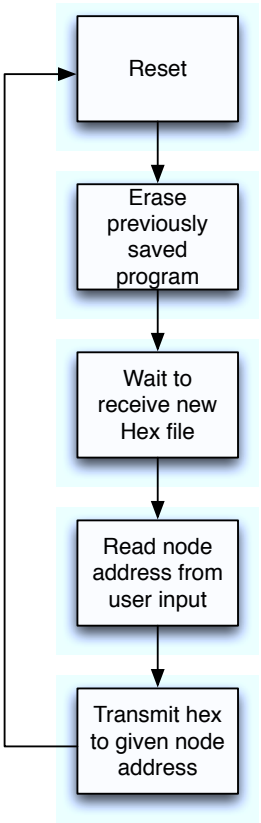


Figure 4.5: The program flow of the gateway firmware

The features that the firmware of the gateway must have are: the file transfer reliability, the low file transfer time and the capability to save large programs in its flash memory. These features were embedded to the devel-

oped firmware with the utilization of a series of mechanisms and techniques. The following section summarizes the functionality of the programming gateway.

PC to Gateway Hex file download

One of the most important functions of the gateway is the download process of the Hex file, from the PC to the gateway's flash memory. The communication interface used is the standard RS232. The file is sent using a terminal application like Hercules, or Windows Hyper Terminal.

To begin with, when the device is reset, the user is prompted to input an Intel Hex file. Once the user sends the file via the terminal and the first byte of the file is received by the gateway, a timer is started. This timer is used in order for the end of file reception to be noticed. Specifically, after every byte is received from the PC, the timer is reset, thus an interrupt marks that enough time has passed before the last byte reception, which in turn means that the file transmission is over. Figure 4.6 depicts the described functionality.

This technique was used because, it is not a good practice to define an escape character (for example EOT) in order to mark the end of the file . That is because, theoretically, the intel Hex file could contain any character, at any place (including the EOT). On the other hand with the technique applied in this thesis, there are no limitations as to which characters the file contains. To conclude, this is the best technique in to download any generic file to the MCU's flash memory.

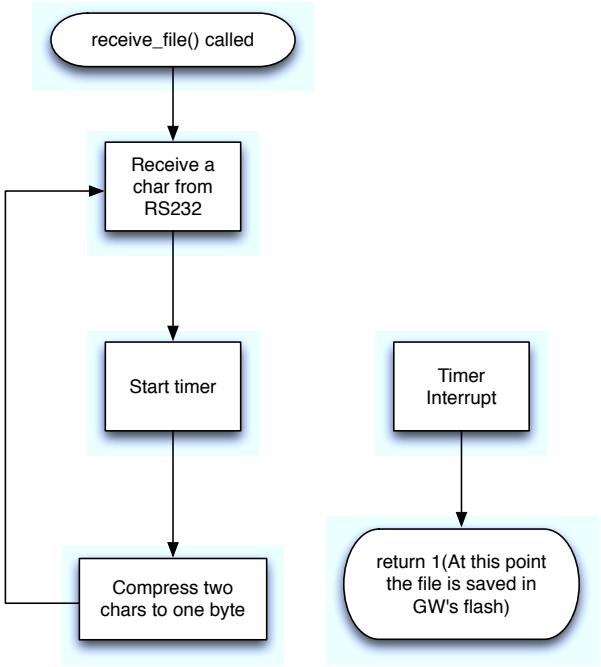


Figure 4.6: Gateway file reception procedure through RS232 interface.

Hex file compression

The size of the C8051F320 flash memory is 16KBytes. The size of the firmware updater is 3.9 KBytes. Thus, only about 12KBytes are left for the Hex file storage in memory.

Given that a typical Hex file of an application with code size about 3 KBytes is 8KBytes[3], a code size constraint appears.

The solution is to somehow compress the file. The Intel Hex format describes every byte of data saved in memory using two characters for each byte. For example byte 0xFE is described by the characters 'F' and 'E'. Therefore in the MCUs flash memory, instead of one byte of data, two are saved, more specifically, instead of the byte 0xFE, the bytes representing characters 'F' and 'E'.

The easy solution for this problem is to save the translation of each byte

[3]The increase in size is due to the extra fields added to the Hex file. For more info see "Intel Hex Code File" section

from ASCII characters to actual binary data. To begin, once a character is received from the RS232 interface, it is converted to its representation as an integer number with the utilization of the toInt() function. For example, the character 'F' is converted to the number 15 and the string "FE" to the number 254. The number 254 can be stored in a variable that is 8 bits long, whereas the string "FE" needs 16 bits of memory space. After the received character is converted, a counter indicating the number of received characters is incremented(in Fig. 4.7 it is named byte_num). If the counter value is an even number, the converted character is saved to the lower 4 bits of an 8 bit buffer and if it is odd, to the higher 4 bits. The separation is done by dividing the counter with 2 and taking the remainder. If it is zero, the counter is an even number, otherwise it is an odd number. This way, pairs of characters are saved in the correct order and only one byte instead of two is used, thus a 2:1 compression ratio is achieved. After each pair is compressed, the buffer that stores the converted number, is saved to the flash memory, and the procedure is repeated until the end of the file.

With the Hex file compression utilization, the file storage capability of the gateway is virtually doubled and therefore, more complex and larger programs can be stored and transferred wirelessly to the WSN. Figure 4.7 depicts this functionality.

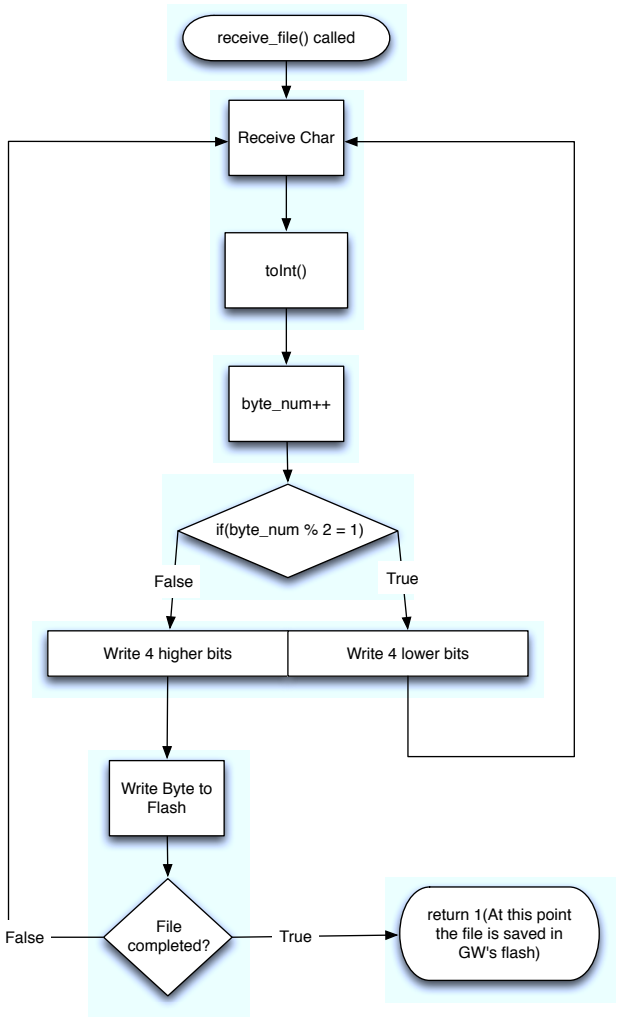


Figure 4.7: Compression of two characters into one byte.

4.3 How to use Over The Air Programming

From the beginning of the OTAP project, one of the major goals was to make the whole procedure as easy as possible. If somehow, the user had to deal with a complex procedure during the wireless download of every program, the whole project would be characterized unsuccessful. Instead, the OTAP is very user friendly both to install and use. Below are the instructions in order for all the components of the OTAP to be installed on a C8051F320/1, using either Keil IDE or Silabs IDE.

4.3.1 Files needed and their description

The OTAP project consists of a number of source files that are necessary for a succesfull compilation and operation. The files are separated in 3 different folders:

- The common_libs folder, which is used for the firmware updater and the bootloader libraries and source files.
- The "bootloader" folder is used for the libraries and the source file containing the main() function of the bootloader.
- The firmware_updater folder which is used for the libraries and the source file containing the main() function of the firmware updater.

4.3.2 Setting up the application to be bootload-able

1. Write the application code, as normal.
2. Relocate the code of the application as per the corresponding the bootloader.h, APP_ADDRESS definition (default 0x1000). Do this by using the CODE("address") directive. For example, for the default set up linking command would be :
   "BL51.EXE TEST_APPLICATION.obj, TO application CODE (1000H)"

   In Keil uVision IDE from main menu goto: Project → Options for Target → "BL51locate" tab → Change the "Code" textfield to APP_ADDRESS value(default 1000H).
   In Silicon Labs IDE : from main menu goto: Project →Tool Chain Integration→ "Linker" tab → "Customize" button → Change the "Code Address" textfield to APP_ADDRESS value(default 0x1000).
3. Include in the application's compilation files the STARTUP.A51 file. Keil strongly recommends that every program should include this file, in uVision and SiLabs IDEs this is done automatically. The file is located at $KeilCompilerInstallationFolder$\C51\LIB\STARTUP.A51.

4. Edit the line of the STARTUP.A51 file from:

```
CSEG    AT      0
?C_STARTUP:     LJMP    STARTUP1
```

to:

```
CSEG    AT      1000H ;(default value)
?C_STARTUP:     LJMP    STARTUP1
```

With the above set up, once a jump is executed to address 0x1000,the application is initialized and started(see section STARTUP.A51 for more information).

5. Instruct the compiler to generate interrupt vectors at the APP_ADDRESS address. Use either the compiler directive INTVECTOR(APP_ADDRESS) or an inline directive using #pragma iv(APP_ADDRESS).
In Keil's uVision IDE from main menu goto : Project → Options for Target → "C51" tab → Tick the "Interrupt vectors at address" box → fill the corresponding textbox with APP_ADDRESS value (default 0x1000).
In Silicon Labs IDE : from main menu goto : Project → Tool Chain Integration→ "Compiler" tab → "Customize" button → add to "Command Line" text field the directive INTVECTOR(APP_ADDRESS) value(default 0x1000).

6. Export the application's Hex file:
In Keil's uVision IDE from main menu goto :Project → Options for Target → "Output" tab → Select "Create executable" → Select create HEX file, with HEX-80 format.
In Silicon Labs IDE : from main menu goto : Project → Target Build Configuration → Select "Generate Hex file" →
The hex file output by this procedure is the one to be downloaded using the master firmware updater.

All the above may seem like a lot of work to be done. On the contrary, the whole procedure does not take more than a minute and it has to be done only once per project.

4.3.3 Setting up and Installing the bootloader

1. In the bootloader.h library set up the MAC_ADDRESS field. This is the node's mac address in order to receive the Intel Hex file from the gateway.
2. Include STARTUP.A51 into the code files.
3. Set up the STARTUP.A51 to jump to address 0x100.
4. Select a MAC_ADDRESS from 0 to 255 in library Link.h.
5. Set up the interrupt vectors to begin at address 0x100.
6. Compile the bootloader.
7. Download the executable.

Once all the above are done, the WSN node is ready to receive code wirelessly. Upon reset, the bootloader is executed and waits for code to be received.

4.3.4 Using master firmware updater to program over the air

1. Compile and download the firmware updater to a RS232 interface compatible node.
2. Connect the gateway to a working RS232 connector.
3. Open a COM terminal (for example Hercules or Hyper Terminal).
4. Turn on the device.
5. Insert the application's Intel Hex file to the COM terminal.[4]

[4]In Hercules, right-click→Insert file. In Hyper Terminal use the "send" button

6. Select a range of MAC addresses for the code to be downloaded. For example an input of 3 to 5 will download the saved program to the nodes with MAC addresses 3 to 5 starting the download from number 3. If the user wants to deliver the application only to node 5, number 5 shall be inserted twice etc.

7. If the message is : "Download completed successfully" then the target node was programmed successfully. Otherwise, programming was not successful. If the programming is not successful then the node shall reset after a timeout and wait for new code download.

Depicted in Fig. 4.8 is the organization of the flash memory contents after the successful installation of the OTAP components, and an application through the bootloader.

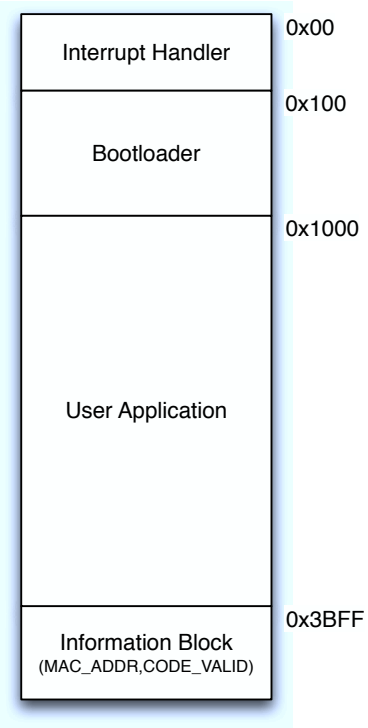


Figure 4.8: The contents of flash memory, after the successful installation of the interrupt handler, the bootloader and application.

4.3.5 Over The Air Programmed "Blinky" Demo ("Hello World" example)

This section will cover the setup and installation of all the OTAP components described above, including a simple bootload-able application. The application's functionality is the blinking of one of the node's LED.

Interrupt pseudo-vector setup

1. Start Keil uVision IDE.
2. Create a new project named "interrupt_vector_project".
3. Select from the database the C8051F320 MCU from Silicon Laboratories.
4. Click no to the pop up menu with the question: "Copy Standard 8051 Startup Code to Project Folder and Add to Project?".
5. Copy the "Interrupt_handler.a" file in the project folder.
6. Expand the folder "Target 1" in the Project Workspace.
7. Right click the "Source Group 1" folder and select the "Add files to Group" option.
8. From the drop down menu "Files of type" select "Asm Source files".
9. Add the "Interrupt_handler.a" file which is included with the files of this thesis.
10. Close the file explorer.
11. Build the target using the corresponding button.
12. Connect a device utilizing the C8051F320 MCU using the SiLabs Debug Adapter.
13. Download the code.

Bootloader

1. Without closing the Keil uVision IDE instance created for the interrupt vector setup, open another instance of the IDE.
2. Create a new project named "Bootloader_project".
3. Make sure that the project will be saved in a folder other than the Interrupt vector's project folder.
4. Copy all the files included in the "common_libs" and the "bootloader" folder in the project folder.
5. With the same steps as above, add all the files that where included in "common_libs" folder except:
   - "receive_packet_csma.c"
   - "send_packet_csma.c"
   - "sleep.c"
   - "channel_clear.c"
6. Add all the files that where included in the "bootloader" folder.
7. Set up the MAC address of the node (constant MAC_ADDRESS in Link.h library) to be the value 1.
8. Relocate the code of the bootloader:
   From the main menu, go to: Project → Options for Target → "BL51locate" tab → Change the "Code" textfield to 100H.
9. Copy the STARTUP.A51 file into the project folder. The file is located at $KeilCompilerInstallationFolder$\C51\LIB\STARTUP.A51.
10. Add the STARTUP.A51 to the project files.
11. Edit the line of the STARTUP.A51 file from:

```
CSEG    AT      0
?C_STARTUP:     LJMP    STARTUP1
```

to:

```
CSEG    AT      100H  ;
?C_STARTUP:     LJMP    STARTUP1
```

12. Set up the interrupt vectors:
    From main menu go to : Project → Options for Target → "C51" tab → Tick the "Interrupt vectors at address" box → fill the corresponding textbox with the value 0x100.

13. Download the code. **In the pop up menu with the question: "Erase memory contents" select NO.** If the contents of the flash memory are erased, the interrupt pseudo-vector must be reinstalled.

Application

1. Without closing the Keil uVision IDE instance created for the interrupt vector and the bootloader setup, open another instance of the IDE.

2. Create a new project named "Application_project".

3. Create a new text file using a text editor and copy the code cited in the appendix.

4. Save the file under the name "Bootloadable_Blinky.c".

5. Copy the file into the project folder.

6. Copy the files listed below from the "common_libs" folder into the project folder:
   - "compiler_defs.h"
   - "C8051F320_defs.h"
   - "FlashPrimitives.h"
   - "F320_FlashPrimitives.c"
7. Add the above files to the compilation list, using the steps described above.
8. Relocate the code of the application:
   From the main menu, go to: Project → Options for Target → "BL51locate" tab → Change the "Code" textfield to 1000H.
9. Copy the STARTUP.A51 file into the project folder. The file is located at $KeilCompilerInstallationFolder$\C51\LIB\STARTUP.A51.
10. Add the STARTUP.A51 to the project files.
11. Edit the line of the STARTUP.A51 file from:

```
CSEG    AT      0
?C_STARTUP:     LJMP    STARTUP1
```

    to:

```
CSEG    AT      1000H   ;
?C_STARTUP:     LJMP    STARTUP1
```

12. Set up the interrupt vectors:
    From main menu go to : Project → Options for Target → "C51" tab → Tick the "Interrupt vectors at address" box → fill the corresponding textbox with the value 0x1000.

13. Export the application's Hex file:
    From the main menu go to: Project → Options for Target → "Output" tab → Select "Create executable" → Select create HEX file, with HEX-80 format.

14. Build the project using the corresponding button. The "Application_project.hex" hex file is the one to be downloaded using OTAP.

Chapter 5

Demos and applications

For better understanding of the telecommunication testbed capabilities, a number of demo code examples have been developed. To begin with, the bootloader and the interrupt handler must first be installed in each of the four iCubes. The procedure is described in section "Setting up and installing the bootloader". In order for the demo to be ready "out of the box", MAC addresses from 3 to 6 must be selected for 4 iCubes in a way that every node will have a unique address. A picture of the setup is depicted in Fig. 5.1.

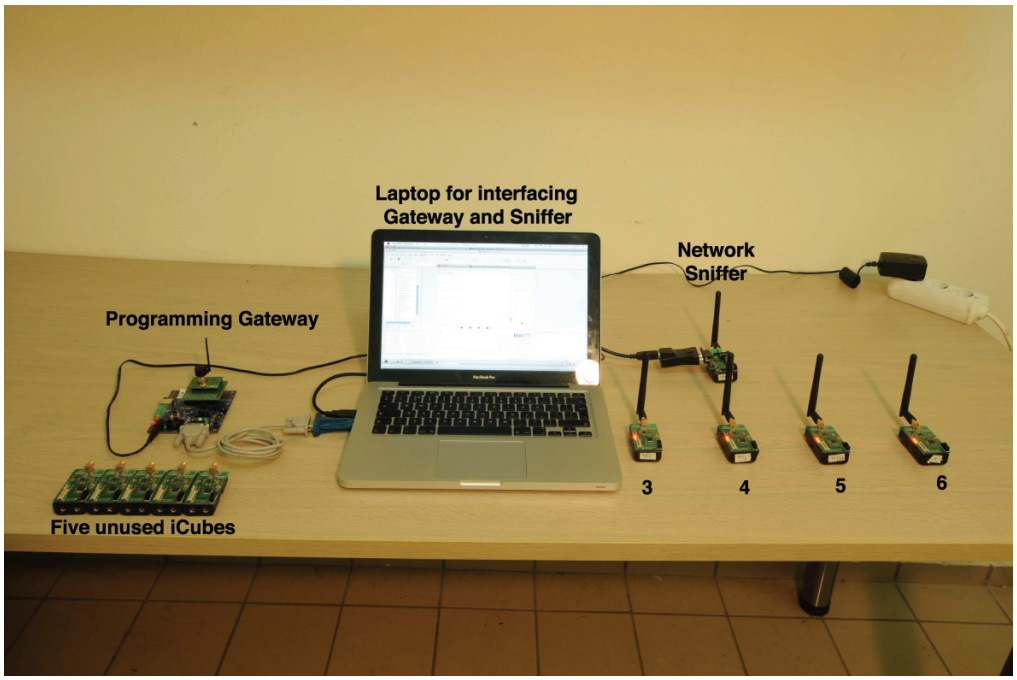


Figure 5.1: Demo setup.

Moreover, the gateway firmware must be installed to a device utilizing the C8051F320/1 (such as the iCube or the C8051F320DK) and connected to a PC running a UART terminal. The host PC must have the Keil 8051 toolchain installed. In section "Setting up the application to be bootloadable", the steps in order for the demos to be bootload-able are listed.

Code-wise, the demo.c and demo_config.h are the main files of the demo. The functionality of the demos is contained in the demo.c file. The code utilizes the preprocessor by using the "#ifdef" instruction, in order to select one out of 5 different demo applications. The selection is made by uncommenting the corresponding line in the demo_config.h library. This way code size optimization is achieved. Furthermore, the demo application is designed in a way that the user will be required to compile and install only once for each demo.

Finally, a technique is presented in order for the application to enter bootloading mode under all circumstances. For this purpose, a timer is utilized (specifically, timer3). The timer is initiated to interrupt every half a second. Then, the application is responsible to count the interrupts and select a threshold (TIMEOUT_RESET) after which it executes the bootloader. This way, even if the application has entered an endless loop or even crashed, OTAP will always be available, either from the normal application procedure, or from the timer3 interrupt handler (which in some demos below is selected as the only way to enter bootloading mode).

5.0.6 Application Description

A brief description of the six different demos is depicted below.

Led blinking ("Hello World")

This is a simple LED blinking application. After all the initializations, the system enters a "for loop" with iterations selected from the ITERATIONS definition. Furthermore, a wait interval between each blinking is selected using the WAIT_TIME definition. After the iterations have surpassed, the application enters the bootloading mode by using the ENTER_BOOTLOADER macro, defined in bootloading_essentials.h. The results of the application with a default set up of the iCube would be for the LED to blink for a number of times described in ITERATIONS and enter bootloading mode. This demo is selected by uncommenting the line "#define LED" in demo_config.h.

Bidirectional relay system

The purpose of this application is the demonstration of the simplicity with which a reliable multihop system that can transfer data from one point to another. The simplicity is referred in terms of code, because the multihop WSN code in this example requires mainly 40 lines of code, since RDT routines are already developed. Once the application is downloaded in all four iCube nodes, a blinking LED from every iCube node, indicates the data direction from the first set up node to the last one (RIGHT_RELAY and LEFT_RELAY utilize opposite directions). After a number of timer3 interrupts have occurred, the application executes the macro to return to bootloading mode. The selection of the demo is done by uncommenting either the line "#define RIGHT_RELAY" or the "#define LEFT_RELAY" in demo_config.h. Figure 5.2 depicts a relay demo execution. One can observe the packet propagation through the relays, since for every successfull packet transmission a LED is turned on.

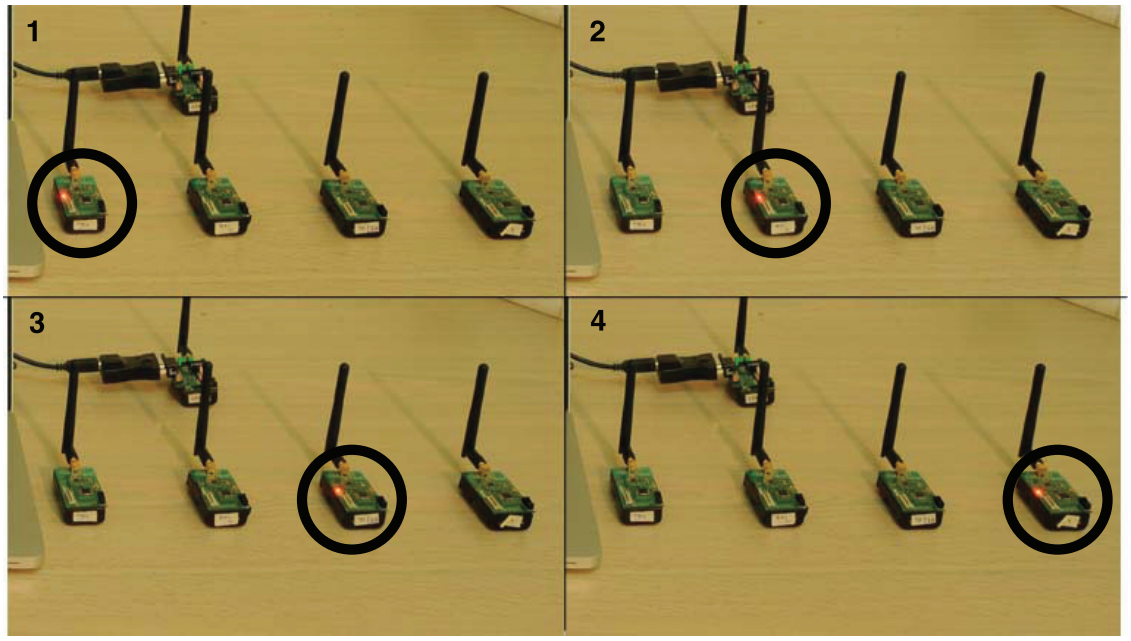


Figure 5.2: Relay demo presentation.

Broadcast system

A typical system in WSNs consists of a set of nodes that receive data and a node that transmits data. This demo is depicting exactly this configuration. The broadcast node is selected from the BROADCAST_NODE definition. Following, the download of the program the broadcast node starts transmitting packets to the receivers. The transmitter and the receiver blink different LEDs in order to be separated visually. Selection of this demo is done by uncommenting the line "#define BROADCAST".

Multiple Access (CSMA/CA) System

Another typical scenario for WSNs is when multiple transmitters engage transmiting to the same receiver. For this scenario, a CSMA/CA algorithm is typically utilized. The application that was developed for demo purposes uses three of the four iCubes as transmitters to a single receiver. All transmitters as well as the receiver utilize the CSMA functions described in section "Carrier Sense Multiple Access with Collision Avoidance". Transmitter-side,

packets are being send between random time intervals. After a succesfull packet transmission has been achieved (acknowledgement received), a LED blinking occurs. Receiver-side, the node is always in receive mode and accepts packets from all mac addresses and returns ACKS to the corresponding nodes while blinking a LED when a reception was succesful. The performance of the demo is not optimal because timeout fine tuning was not performed as this code is only a proof of concept demo for the OTAP.

5.0.7 Network debugging tool

During the development of the telecommunication testbed, there was need for recording and logging the packet streams throughout the network. For the purposes of this task, firmware for packet sniffing was developed. With the utilization of the packet sniffer, the packet flow can be recorded, thus the telecommunication engineer is reinforced with a valuable network debugging and data logging tool.

The functionality of the sniffer is fairly simple. The WSN node equipped with the sniffer firmware, utilizes the primitive function of packet reception in order to receive every transmitted packet of the network. The packet information is saved in an array. Particularly, the type, the transmitter and receiver of the packet are stored and presented to the user for further analysis.

Followingly, the instructions for the operation of the packet sniffer are depicted. To start with, the user must first install the firmware to a WSN node capable of communicating with a PC using a RS232 interface. After the installation, and the initialization of the sniffer node, the user will be prompted to start the packet reception by sending a special character through the interface (default is 'b'). At this stage the user should start the operation of the network and begin the packet sniffing. If a number of packets defined in PACKET_BUFFER_SIZE definition are received, or user inserts character 's', the packet sniffing is stopped and the information of the collected packets are presented to the user. Below, an example of the printouts of the network debugging tool is depicted:

Fig. 5.3 depicts the sniffer printouts after the successful reception of 10

packets from the relay system described in the demo section. The packet flow is easily observable from the node with address 3 to 6 as well as the acknowledgement exchange throughout the procedure.

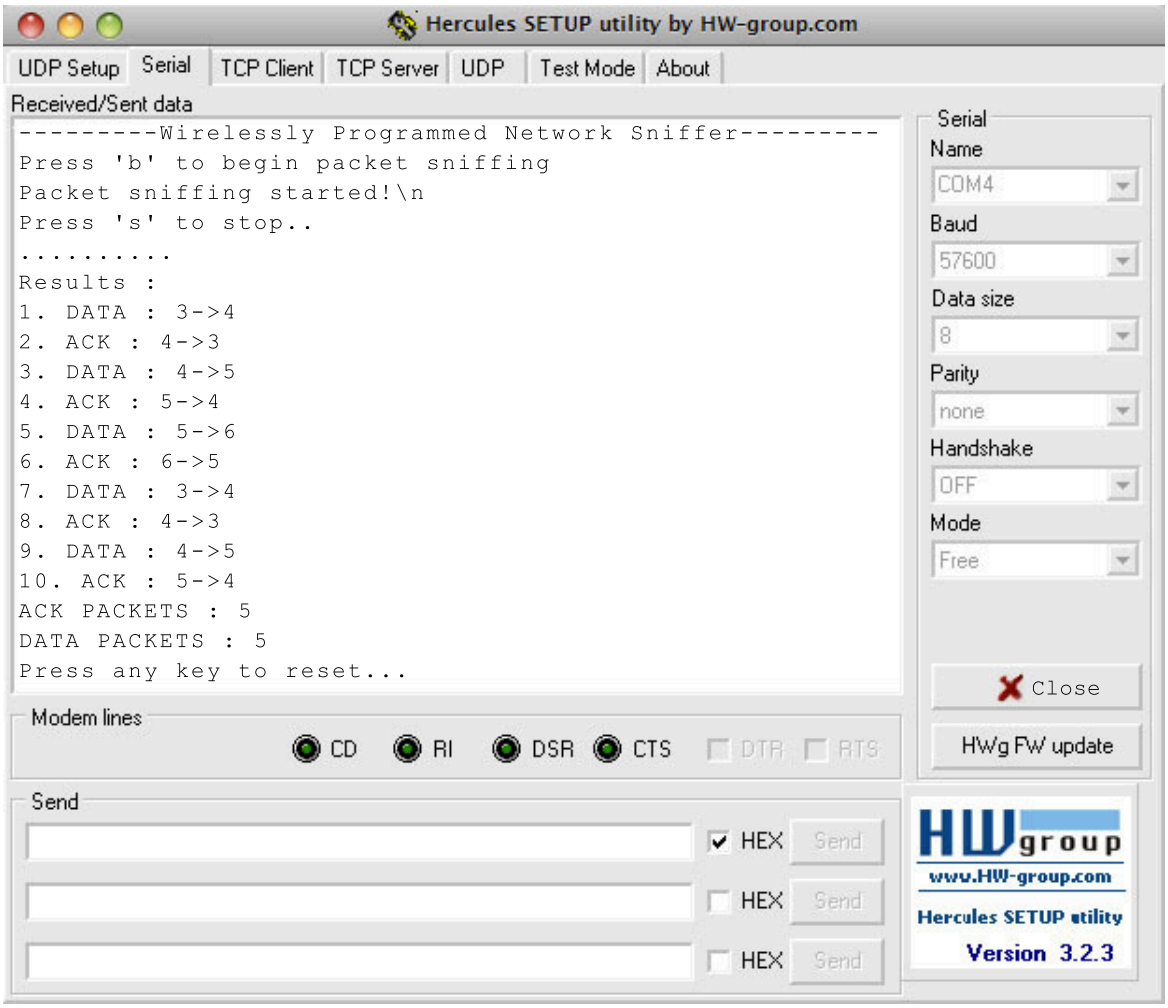


Figure 5.3: Sniffer functionality with relay system.

Chapter 6

Conclusion and future/ongoing work

6.1 Future/Ongoing Work

For this thesis, a OTAP methodology was developed from scratch. The main components developed throughout the thesis are the Over The Air Programming capability, the XTboard, the Reliable Data Transmission routines and the programs that demonstrate the testbed potential.

There is a lot of ongoing and future work in order for the WSN under development to be an even more competitive product compared to prior art. The projects that are either programmed for future work or currently under development are summarized below.

iCube2

The iCube2 is a future project that involves the design and implementation of a new wireless sensor network node. The new node will consist of a more advanced and lower power consumption MCU, which utilizes modules such as a Real Time Clock that provide the engineer with further functionalities and capabilities.

Ultra low power OTAP

Currently, Over The Air Programming is a fairly high power consuming procedure. Speciffically, when the node is receiving code wirelessly consumes around 80mW of power. The power consumption of the process can be reduced to the order of a few hundreds microwatts by utilizing "Wake On Radio", "Periodic Sleep" and other techniques for minimizing the power consumption of a WSN node. Such techniques shall be applied to the OTAP in the future.

Multihop OTAP

The developed OTAP is currently capable of programming nodes that are within the range of the gateway, i.e within one hop. This is a critical constraint for a wirelessly programmed WSN. For this reason, multihop OTAP capability is currently under development in order to overcome this constraint. Multihop OTAP will be based on the same principles with the one already developed, with the addition of a packet routing or flooding technique that will enable the programming of nodes with no access to the gateway.

Energy Harvesting

Energy harvesting is the process with which energy derived from external sources is captured, and stored into energy containers such as batteries or ultra capacitors. Such energy sources are the sun rays, the wind or even RF power from ambient signals (such as UHF). For the exploitation of these environmental energy soirces, special modules are currently under development. The modules include boost converters [7], rectennas [8], custom wind-mills [9] and utilization of advanced energy storage solutions, such as those in [10].

6.2 Challenges during development

During the development of all the above middleware and hardware there were certain problems. Some were critical for the development process and others minor. Both are stated below.

The most important of the problems was the lack of a usable debugger for networking applications. The debugger provided by Silicon Labs, unfortunately is neither easy to use nor capable of debugging networking applications. Therefore all the debugging procedures where done utilizing LED blinking, oscilloscopes and UART printouts (which for most bugs do not work). The above debugging tools are clearly not sufficient for a developer that needs to know exactly what is happening with interrupts and the contents of the flash memory in real time while packets are being received and sent wirelessly.

Another critical challenge was the lack of the the fact that OTAP application was developed from ground up using custom primitive functions and trial-and-error practices. This process helped a lot to educate the author and to develop an application that is fresh and easily updatable.

Moreover, from the beginning of the OTAP project, a challenge was to set up three different applications to be installed in the same memory. For the purposes of this challenge, the whole project was separated into three different Keil uVision IDE sub-projects which were edited and installed simultaneously. This means that three different projects had to be debugged, set up and installed as one. If one of these was buggy, everything failed. For example, if the pseudo-interrupt vector did not redirect the interrupts correctly, then a difficult to find bug would appear either on the bootloader, or in the application.

6.3 Conclusion

The telecommunication testbed developed is a high quality engineering tool for the fast deployment of research projects and applications. The capability of remote WSN programming is available through a simple installation and deployment process, thus providing the engineer the ability to update the network within seconds. Moreover, the XTboard is an essential interfacing tool for the iCubes node in order for the latter to be transformed to a fully functional sensor node capable of transferring data to a PC. Finally, the demos described in section "Demos and Applications" speed up the learning process of the tool and are used to demonstrate the capabilities of the testbed.

Appendix A

Gateway Code

```
1  void main(void){
2
3    // Initialization routines called here.
4    Init_mcu_and_peripherals();
5
6    //Delete the previous program from gateway memory
7    erase_flash();
8
9    puts("Insert HEX :");
10   // Call receive_file, which is the file
11   // reception and compression function
12   if(receive_file()){
13     puts("Done");
14   }else{
15     puts("Error on file reception\nRestarting...");
16     halWait(60000);
17     halWait(60000);
18     RSTSRC = 0x10;
19   }
20
21   // Read the address range of
22   // the nodes that will receive the file
23   puts("Insert mac address of the first node to transmit :");
24   from = getchar() - 48;
25   puts("Insert mac address of the last node to transmit :");
26   to = getchar() - 48;
27
28   // If from > to then send from large address to small
29   if(from > to){
30     step = -1;
31   }else if(from < to){
32     step = 1;
```

```
33    }else{
34      step = 1;
35    }
36
37    puts("\nTransmitting file.");
38    for( node_num = from //
39    ; node_num != to+step //
40    ; node_num = node_num+step ){
41
42      // printout
43      putchar(node_num + '0');
44      putchar('\n');
45
46      // Here transmit_file is called
47      // This function utilizes the RDT functionality
48
49      if(transmit_file((UINT8)node_num)){
50        puts("\nTransmition Success!");
51      }else{
52        //If transmission failed, reset
53        puts("\nTransmit Failed!\n");
54        RSTSRC = 0x10;
55      }
56    }
57
58    // If all nodes have received the file, reset
59    puts("\nResetting...\n");
60    RSTSRC = 0x10;
61  }
```

Appendix B

Blinky code

```
1  //-----------------
2  // F320_Blinky.c
3  //-----------------
4  // This program flashes the green LED on the
5  //C8051F32x target board.
6  // After the LED blinking the node execution is transfered
7  // in bootloading mode.
8
9
10 //-----------------
11 // Includes
12 //-----------------
13
14 #include "../common_libs/compiler_defs.h"
15 #include "../common_libs/C8051F320_defs.h"
16 #include "../common_libs/F320_FlashPrimitives.h"
17
18 //-----------------
19 // Global CONSTANTS
20 //-----------------
21
22 #define UPDATER_ADDRESS 0x100
23 #define CODE_VALID_ADDRESS  0x3BFF
24
25 // LED1='1' means ON
26 SBIT(LED1, SFR_P2, 7);
27 // LED2='1' means ON
28 SBIT(LED2, SFR_P2, 6);
29
30 //-----------------
31 // Function PROTOTYPES
32 //-----------------
```

```
33
34 void SYSCLK_Init (void);
35 void PORT_Init (void);
36 void halWait(int timeout);
37
38
39 //-----------------
40 // MAIN Routine
41 //-----------------
42
43 void main (void)
44 {
45   int i;
46   // Disable watchdog timer
47   PCA0MD &= ~0x40;
48   //raise the now_running_app flag
49   PSW |= 0x02;
50   // Initialize system clock
51   SYSCLK_Init ();
52   // Initialize crossbar and GPIO
53   PORT_Init ();
54
55   while (1){
56
57     while(1){;}
58     for(i = 0; i < 25 ; i++){
59       halWait(40000);
60       LED1 = !LED1;
61     }
62
63
64     //Unset the code validity bit
65     FLASH_ByteWrite(CODE_VALID_ADDRESS , 0);
66     //Soft reset
67     RSTSRC = 0x10;
68
69
70   }
71
```

```
72 }
73 // Delay function
74 void halWait(int timeout) {
75   do {
76     _nop_();
77     _nop_();
78     _nop_();
79     _nop_();
80     _nop_();
81     _nop_();
82     _nop_();
83     _nop_();
84     _nop_();
85     _nop_();
86     _nop_();
87     _nop_();
88     _nop_();
89     _nop_();
90   } while (--timeout);
91 }// halWait
92
93 //-----------------
94 // SYSCLK_Init
95 //-----------------
96 void SYSCLK_Init (void)
97 {
98   // Configure internal oscillator for
99   OSCICN = 0x80;
100  // Enable missing clock detector
101  RSTSRC = 0x04;
102 }
103
104 //-----------------
105 // PORT_Init
106 //-----------------
107 void PORT_Init (void)
108 {
109  // Enable P2_6 as a push-pull output
110  P2MDOUT |= 0x40;
```

```
111     // Enable P2_7 as a push-pull output
112   P2MDOUT |= 0x80;
113
114   // Enable crossbar and weak pull-ups
115   XBR1 = 0x40;
116 }
117
118 //-----------------
119 // End Of File
120 //-----------------
```

Appendix C

Demo codes

C.1 LED Blinking

```
1  #ifdef LED
2  #define SPAM_WAIT 20000
3  #define ITERATIONS 100
4  #define TIMEOUT_RESET 1000
5            for(i = 0 ; i < ITERATIONS ; i++){
6              halWait(SPAM_WAIT);
7              BLINK6;
8            }
9      START_BOOTLOADER();
10 #endif
```

C.2 Relay system with direction from node 6 to 3

```
1  #ifdef RIGHT_RELAY
2  #define SPAM_WAIT 30000
3  #define TIMEOUT_RESET 700
4       while(1){
5
6          if(mac == TX1){
7            //SPAM_WAIT*6 results in an overflow
8            //thus 6 calls of halWait are used
9            halWait(SPAM_WAIT);
10           halWait(SPAM_WAIT);
11           halWait(SPAM_WAIT);
12           halWait(SPAM_WAIT);
```

```
13            halWait(SPAM_WAIT);
14            halWait(SPAM_WAIT);
15            if(RDTsend_packet_rdt(RX1)){
16              ON6;
17              halWait(SPAM_WAIT);
18              OFF6;
19            }
20          }
21
22          if(mac == RX1){
23            if(RDTreceive_packet_rdt(TX1,20)){
24              halWait(SPAM_WAIT);
25              if(RDTsend_packet_rdt(TX2)){
26                ON6;
27                halWait(SPAM_WAIT);
28                OFF6;
29              }
30            }
31          }
32
33          if(mac == TX2){
34            if(RDTreceive_packet_rdt(RX1,20)){
35              halWait(SPAM_WAIT);
36              if(RDTsend_packet_rdt(RX2)){
37                ON6;
38                halWait(SPAM_WAIT);
39                OFF6;
40              }
41            }
42          }
43
44          if(mac == RX2){
45
46            if(RDTreceive_packet_rdt(TX2,20)){
47              halWait(SPAM_WAIT);
48              ON6;
49              halWait(SPAM_WAIT);
50              OFF6;
51            }
```

```
52          }
53      }
54  #endif
```

C.3 Relay system with direction from node 3 to 6

```
1
2   #ifdef LEFT_RELAY
3   #define SPAM_WAIT 30000
4   #define TIMEOUT_RESET 700
5
6       while(1){
7
8           if(mac == RX2){
9             halWait(SPAM_WAIT);
10            halWait(SPAM_WAIT);
11            halWait(SPAM_WAIT);
12            halWait(SPAM_WAIT);
13            halWait(SPAM_WAIT);
14            halWait(SPAM_WAIT);
15            if(RDTsend_packet_rdt(TX2)){
16              ON6;
17              halWait(SPAM_WAIT);
18              OFF6;
19            }else{
20              //                P2_7 = !P2_7;
21            }
22          }
23
24          if(mac == TX2){
25            if(RDTreceive_packet_rdt(RX2,20)){
26              halWait(SPAM_WAIT);
27              if(RDTsend_packet_rdt(RX1)){
28                ON6;
29                halWait(SPAM_WAIT);
30                OFF6;
```

```
31              }
32            }
33          }
34
35          if(mac == RX1){
36
37            if(RDTreceive_packet_rdt(TX2,20)){
38              halWait(SPAM_WAIT);
39              if(RDTsend_packet_rdt(TX1)){
40                ON6;
41                halWait(SPAM_WAIT);
42                OFF6;
43              }
44            }
45          }
46
47          if(mac == TX1){
48
49            if(RDTreceive_packet_rdt(RX1,20)){
50              halWait(SPAM_WAIT);
51              ON6;
52              halWait(SPAM_WAIT);
53              OFF6;
54            }
55          }
56      }
57  #endif
```

C.4 Broadcast system

```
1
2   #ifdef BROADCAST
3   #define SPAM_WAIT 45000
4   #define TIMEOUT_RESET 700
5   #define BROADCAST_NODE TX1
6   #define TIMEOUT_RX 250
7
8       if(mac == BROADCAST_NODE){
```

```
9         txBuffer[INDEX_TX_ISACK] = 0;
10        txBuffer[INDEX_TX_FROM_MAC] = mac;
11        txBuffer[INDEX_TX_TO_MAC] = 255;
12      }
13      while(1){
14
15        if(mac == BROADCAST_NODE){
16          halRfSendPacket(txBuffer, sizeof(txBuffer));
17          BLINK7;
18          halWait(SPAM_WAIT);
19        }else{
20          if(halRfReceivePacket(rxBuffer,&length,TIMEOUT_RX)){
21            BLINK6;
22          }
23        }
24      }
25  #endif
```

C.5 CSMA/CA system

```
1
2
3   #ifdef  CSMA
4   #define TIMER_RELOAD 100
5   #define CS_TIMEOUT 6
6   #define ACK_TIMEOUT 10
7   #define UNTIL_RECEPTION 0
8   #define TIMEOUT_RESET 700
9   #define RECEIVER TX1
10  #define PRINTOUT
11  #define RAND_ON
12
13      if(mac == RECEIVER ){
14
15        if(receive_packet_csma(1,ACCEPT_FROM_ALL,10,CS_TIMEOUT)){
16          BLINK7;
17        }
18
```

```
19      }else{
20        if(send_packet_csma(\
21        RECEIVER,\
22        TIMER_RELOAD,\
23        CS_TIMEOUT,\
24        ACK_TIMEOUT,\
25        1)){
26          halWait(10000*((BYTE)rand()));
27          BLINK6;
28        }
29      }
30  #endif
```

C.6 Demo code configuration library

```
1
2
3   //DEMOS
4   //Uncomment one at a time
5   //#define LED
6   //#define RIGHT_RELAY
7   //#define LEFT_RELAY
8   //#define BROADCAST
9   //#define ENDLESS_LOOP
10  //#define CSMA
11
12  #define BLINK7 P2_6 = !P2_6
13  #define BLINK6 P2_7 = !P2_7
14  #define ON7 P2_6 = 1
15  #define ON6 P2_7 = 1
16  #define OFF7 P2_6 = 0
17  #define OFF6 P2_7 = 0
18
19  //uncomment to enable printouts
20  //MISC SETUP
21  //#define PRINTOUT
```

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