Introduction To IoT Reverse Engineering

with an example on a home router

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What we will talk about …

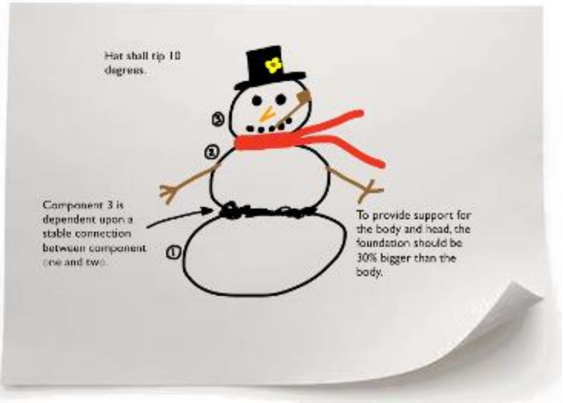
- Introduction
- Information gathering
- Emulation environment using QEMU
- Analyze how the device works
- Modify the firmware

Engineering

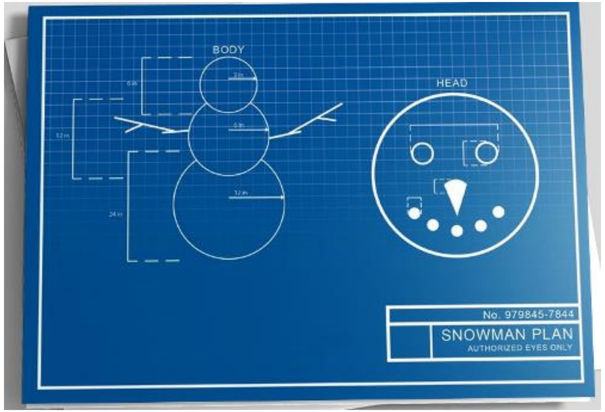
What is "*engineering*"? "*the science of making things*"

- Define "*product requirements*"
- Design the product
- Build or manufacture the product

Requirements



Design Blueprint



Product

What is ”*reverse engineering*”?

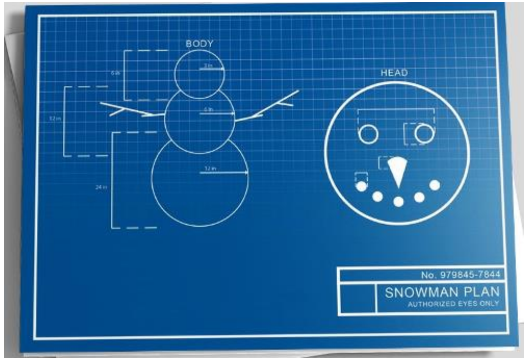
- It is the ”*engineering*” process done in reverse order and, usually, with limited scope

What is this example project “*limited scope*”?

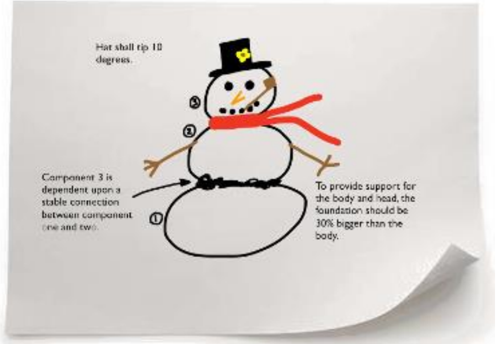
- modify the router firmware to add features and programs

Product

Design Blueprint



Requirements



Information Gathering

- Who makes the device?
- Is there an ODM (*Original Design Manufacturer*)?
- Open the case
- Identify main device components
- Locate UART and possibly JTAG Interfaces
- Get the firmware and the root file system

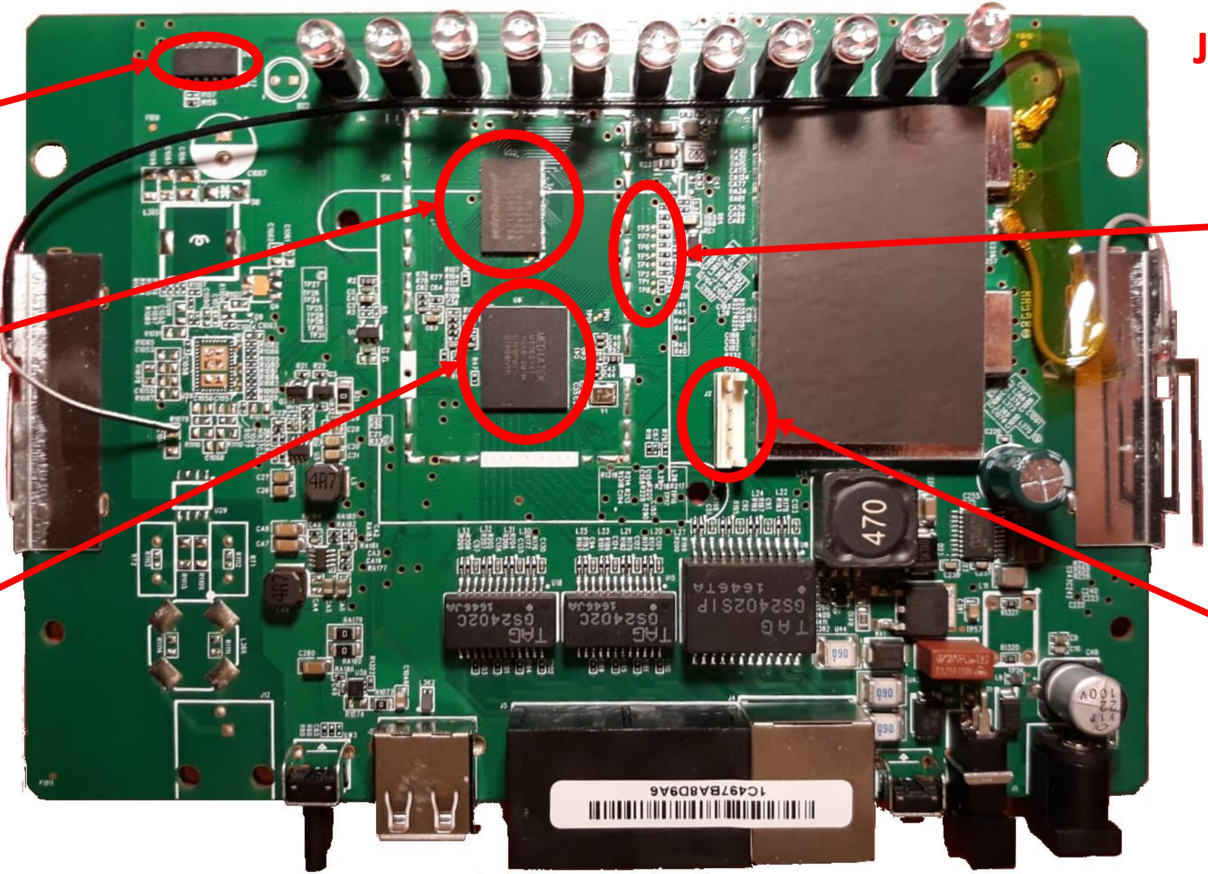
Gemtek/Linkem
WVRTM-127ACN
example home router

Mainboard Top

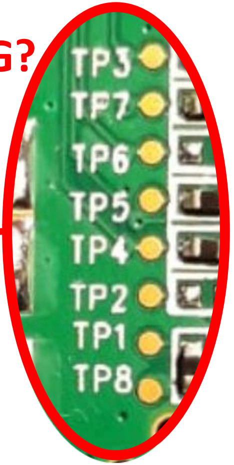
74HC164

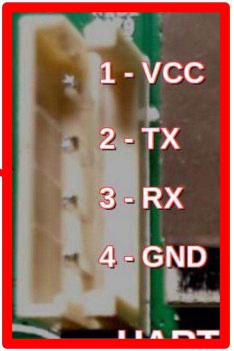
RAM 128Mb
Winbond
W971GG6SB

System On
Chip
Mediatek
MT7621AT



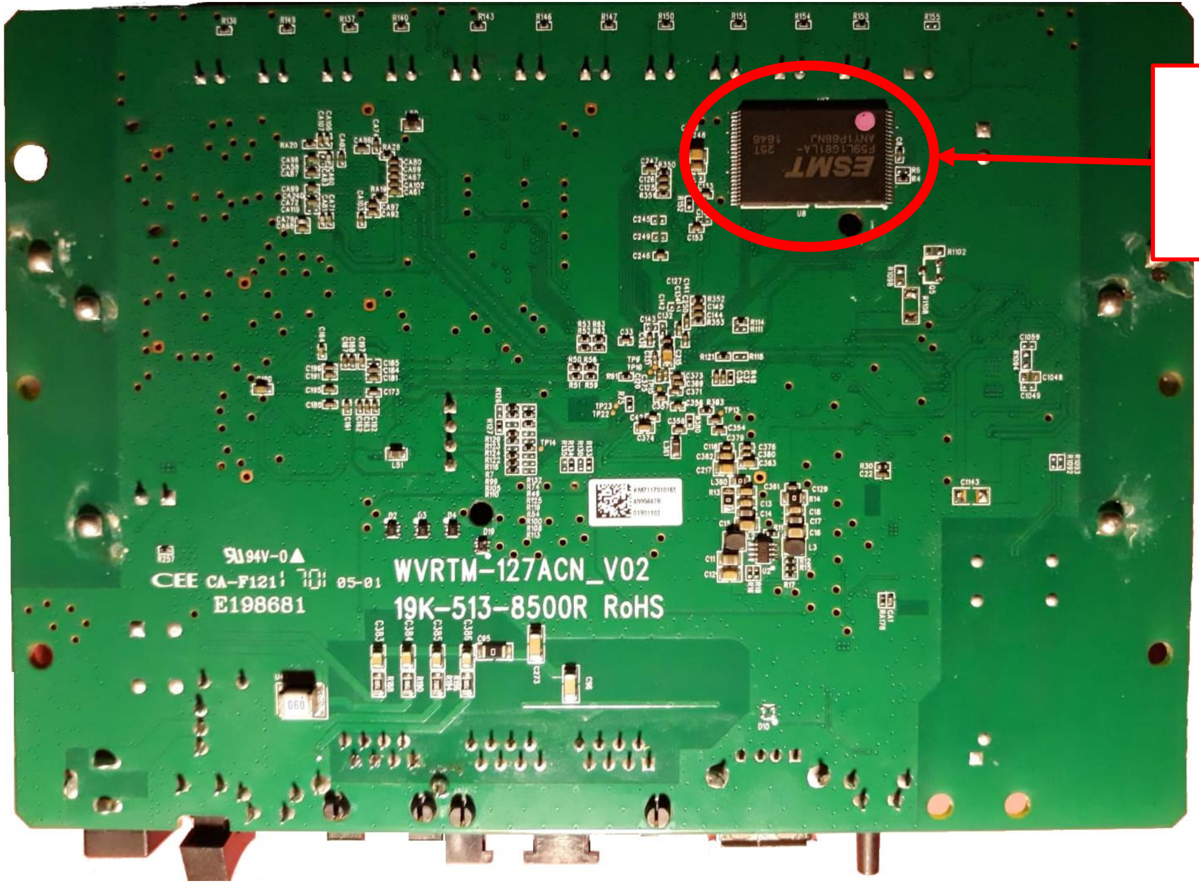
JTAG?





UART

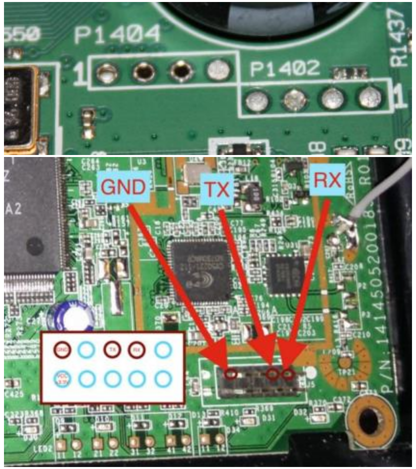
Mainboard Bottom



128Mb
NAND Flash
F59L1G81LA

Locate the UART interface

UART on various boards



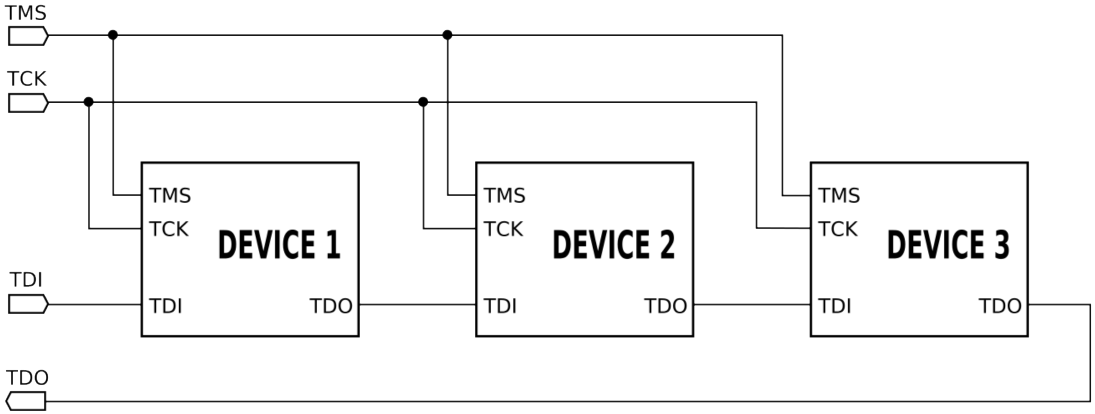
- Search on Internet
- Identify potential serial headers candidates
- Sometimes marked in the PCB's silkscreen
- Usually 4 pins: Vcc, Gnd, Tx, Rx
- Use a multimeter to find potential candidates
- Locate pins on SOC and follow PCB traces
- Use tools like Jtagulator
- Oscilloscope or Logic Analyzer to locate Tx (a little overkill)

Gemtek router
UART Pin Candidates

Pin	R_{GND}	R_{VCC}	V	Notes
1	29KΩ	0Ω	3.3V	Vcc
2	4.7KΩ	33kΩ	3.3V	0-3.3V on boot (TX?)
3	∞Ω	∞Ω	3.3V	RX?
4	0Ω	29KΩ	0V	Gnd

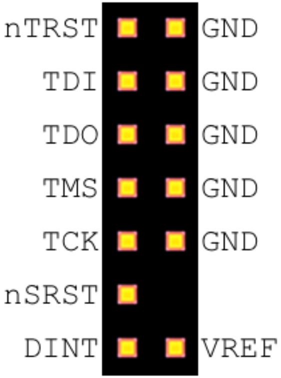
The JTAG interface

- JTAG is an industry standard for testing PCB after manufacture
- Allows access to read/write flash memory contents and can be used as a primary means for an in-circuit emulator
- Multiple devices are daisy-chained together
- Pins:
  TCK *test clock*
  TDI *test data in*
  TDO *test data out*
  TMS *test mode sel.*
  TRST *test reset (opt.)*



Locate the JTAG interface

- No standard pinout, but few popular pinouts: http://www.jtagtest.com/pinouts/
- Search on the Internet
- Look for headers labeled TCK, TDI, TDO, TMS
- Look for 1x5/6, 2x5, 2x7, 2x10 pin headers and, with a multimeter,
  - Look for GND and VCC and compare to popular pinouts
  - Often there are pullups (1-100k) for TMS, TDI and TRST, TRST can also be pulled low
  - TDO should be high impedance
- Locate pins on SOC and follow PCB traces
- Use tools like Jtagulator



Connect the serial cable

Why repopulate the interfaces?

- UART (Serial Interface)
  - Watch what is printed on the serial console during the boot cycle and find bootloader and OS version
  - Watch the firmware upgrade cycle
  - Use a USB TTL serial adapter and a terminal emulator on the PC
- JTAG
  - Read the firmware out of the flash eeprom
  - Break into the boot cycle and use JTAG to do ”*in circuit debugging*”
  - Attach an interface board, like *Bus Pirate*, to the JTAG interface
  - Use *OpenOCD*, to dump eeprom and to do ”*in circuit debugging*”

Getting the firmware file

- Follow the easiest path first
- If the supplier has a website with firmware updates go and download the firmware file
- If the firmware update can be downloaded directly only by the device, sniff the communication with *wireshark*
- If the bootloader has a CLI and a dump flash command, use the bootloader CLI
- Otherwise, download the eeprom image through the JTAG connector using Bus Pirate and OpenOCD

Assignment 1
get info from what is printed during boot

- Bootloader name and version
- System On Chip (SOC) model and architecture
- Amount of RAM and EEPROM installed
- Linux Kernel version
- File system types
- NAND partition details
- Init process software
- Is the bootloader CLI available?

Download boot.log.gz from:
http://va.ler.io/ws
or
http://116.203.78.185

Boot output on serial console - 1

```
U-Boot 1.1.3 (Oct 23 2015 - 16:03:05)
...
mtd->writesize=2048 mtd->oobsize=64,  mtd->erasesize=131072
...
 Ralink UBoot Version: 4.3.2.0
 ASIC MT7621A DualCore (MAC to MT7530 Mode)
  ...
##### The CPU freq = 880 MHZ ####
estimate memory size =128 Mbytes
...
NAND device: Manufacturer ID: 0xc8, Chip ID: 0xd1 (Unknown
NAND 128MiB 3,3V 8-bit)
```

Boot output on serial console - 2

U-Boot Menu

```
Please choose the operation:
   1: Load system code to SDRAM via TFTP.
   2: Load system code then write to Flash via TFTP.
   3: Boot system code via Flash (default).
   4: Entr boot command line interface.
   9: Load Boot Loader code then write to Flash via TFTP.
```

Boot output on serial console - 3

Booting kernel details

```
3: System Boot system code via Flash.
## Booting image at 81000000 ...
   Image Name:   =01.01.02.090
   Image Type:   MIPS Linux Multi-File Image(lzma compressed
   Data Size:    19062732 Bytes = 18.2 MB
   Load Address: 80001000
   Entry Point:  8000f540
   Image 0:  1966004 Bytes =  1.9 MB
   Image 1: 17096704 Bytes = 16.3 MB
   Verifying Checksum ... OK
   Uncompressing Multi-File Image ... OK
   ## Transferring control to Linux (at address 8000f540) ...
   ## Giving linux memsize in MB, 128
   Starting kernel ...
```

Boot output on serial console - 4

Kernel, CPU and root file system details

```
Linux version 2.6.36 …(gcc 4.5.4 (Buildroot 2015.02-svn12502)
 ...
Kernel command line: console=ttyS0,115200n8
console=ttyS0,115200n8
 ...
CPU revision is: 0001992f (MIPS 1004Kc)
 ...
squashfs: version 4.0 (2009/01/31) Phillip Lougher
 ...
RAMDISK: squashfs filesystem found at block 0
RAMDISK: Loading 16696KiB [1 disk] into ram disk... done.
VFS: Mounted root (squashfs) readonly on device 1:0.
```

Boot output on serial console - 5

NAND Partitions

```
[    2.760000] Creating 9 MTD partitions on "MT7621-NAND":
[    2.764000] 0x000000000000-0x000000100000 : "Bootloader"
[    2.772000] 0x000000100000-0x000000200000 : "Bootloader2"
[    2.776000] 0x000000200000-0x000000300000 : "Config"
[    2.784000] 0x000000300000-0x000000580000 : "Env1"
[    2.788000] 0x000000580000-0x000000800000 : "Env2"
[    2.792000] 0x000000800000-0x000002800000 : "Kernel"
[    2.800000] 0x000002800000-0x000004800000 : "Kernel2"
[    2.804000] 0x000004800000-0x000006400000 : "Storage1"
[    2.808000] 0x000006400000-0x000007f80000 : "Storage2"
```

Boot output on serial console - 6

UBIFS read/write File System

```
init started: BusyBox v1.23.1 (2016-01-22 15:02:56 CST)
...
UBI: attached mtd8 to ubi8
UBI: MTD device name:                    "Storage2"
...
UBIFS: mounted UBI device 8, volume 0, name "mtd8"
UBIFS: file system size: 23744512 bytes (23188 KiB, 22 MiB,
…
UBIFS: journal size:       1142784 bytes (1116 KiB, 1 MiB)
UBIFS: default compressor: lzo
...
```

Boot output on serial console - 7

TR069 protocol and login prompt

```
[TR069_A4] ACS Connect Failed: … acs.linkem.com[TR069_A4]
[TR069_A4] ACS Connect Failed: … acs.linkem.com[TR069_A4]
...
 buildroot login: admin
 Challenge code:
mZkq7ohJax+YwmOgTHSTRwdKotmQkVqX4tOZQt0ypomSRQz6RkKsj/TAOD3
focWSRrrIUFEeqQaShH3+xZHFe8znuCYBfZrdXdyzTShql0OpT+i62XRwLb
ptcOpWX6dANtb612WXLEFaLfL4yEBDbChVSKVrre9RsrKFL4YblAPKGDQEd
lC2ZDX0TNQOgWKkarAAVgHO5LnOdgyPT4SakKzZfH2JmYEbRhbCBRTVhYkq
NqT0lI5QKcWwYURE0foJc7+YCm7NU+MPzyt/3tEl5l8JjjZLxgg8p2xBX9/
pcE3rtIoUWGT6/2l5hN6eA
 Authentication code: admin
 Fail!
```

Boot Loader Main Menu


```
MT7621 # help
?         - alias for 'help'
bootm     - boot application image from memory
go        - start application at address 'addr'
help      - print online help
md        - memory display
mdio      - Ralink PHY register R/W command !!
mm        - memory modify (auto-incrementing)
nand      - nand command
nm        - memory modify (constant address)
printenv- print environment variables
reset     - Perform RESET of the CPU
saveenv - save environment variables to persistent storage
setenv    - set environment variables
tftpboot- boot image via network using TFTP protocol
version - print monitor version
```

Boot Loader Nand Menu

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```
MT7621 # help nand
nand nand usage:
  nand id
  nand read <flash_offset> <len> [dst_addr]
  nand write <flash_offset> <src_addr> <len>
  nand erase_write <flash_offset> <src_addr> <len>
  nand page <number>
  nand erase <addr> <len>
  nand erase_ignore_bad_block <flash_offset> <len>
  nand list_bad_block
  nand oob <number>
  nand dump
  nand init
```

Boot Loader Env Variables

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```
MT7621 # printenv
...
fileaddr=81000000
ipaddr=10.10.10.123
serverip=10.10.10.3
...
mtddevnum=6
root_chain_cert=QlpoOTFBWSZTWYDk05wABNX/lOiQAEDAC//iP///
...


...


Environment size: 3108/131067 bytes
```

Bootloader CLI: booting from NAND

```
MT7621 # nand read 800000 2000000 81000000
read len: 33554432
0x00800000 copy to 0x81000000
MT7621 # bootm
## Booting image at 81000000
   Image Name:   =01.01.02.090
   Image Type:   MIPS Linux Multi-File Image (lzma compr…
   Image 0:  1966004 Bytes =  1.9 MB
   Image 1: 17096704 Bytes = 16.3 MB
   Verifying Checksum ... OK
   Uncompressing Multi-File Image ... OK
   ## Transferring control to Linux (at address 8000f540)
   ## Giving linux memsize in MB, 128
   Starting kernel ...
```

Memory Address

Length 2:00:00:00

NAND Address

```
  80:00:00 "kernel"  partition
2:80:00:00 "kernel2" partition
```

Bootloader CLI: booting from TFTP Server

```
MT7621 # tftpboot 81000000 kernel.bin
...
TFTP from server 10.10.10.3; our IP address is 10.10.10.123
Filename 'kernel.bin'.
...
############################################################ ...
32 MB reveived
...
MT7621 # bootm
## Booting image at 81000000 ...
   Image Name:   =01.01.02.090
## Transferring control to Linux (at address 8000f540) ...
## Giving linux memsize in MB, 128
Starting kernel ...
```

Memory Address

Getting EEPROM firmware - 1

```
MT7621 # nand page 0
page 0x0:
27 05 19 56 42 ee ee b3 56 29 e9 b9 00 02 25 fc a0 20 00 …
4e 41 4e 44 20 46 6c 61 73 68 20 49 00 00 00 00 00 00 00 …
...
00 00 5b af 21 d8 e0 03 21 f8 c0 03 08 00 60 03 00 00 00 …
00 00 00 00 00 00 00 00 08 00 c1 28 2e 00 20 14 21 10 80 …
#
oob:
ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff …
db 15 b2 47 1b fc f3 ff 7e dd 57 a5 d2 3d fb ff 5e 31 c4 …
```

Getting EEPROM firmware - 2

Expect script

```
expect "Load Boot Loader code then write to Flash via TFTP"
send "4"
for {set i 0} {$i<65537} {incr i} {
    expect "MT7621 # "
    set ihex [format %x $i]
    send "nand page $ihex\r"
}
```

Execute the script and convert to bin

```
$ ./serial-flash-dump.expect /dev/ttyUSB0  | tee eeprom.txt
$ cat eeprom.txt | ./hexdump2bin.pl  > eeprom.bin
SUCCESS 65536 pages dumped, 134217728 bytes
```

Splitting EEPROM into partitions

```
dd if=ee.bin of=01-bootloader  bs=1024 skip=0      count=1024
dd if=ee.bin of=02-bootloader2 bs=1024 skip=1024   count=1024
dd if=ee.bin of=03-config      bs=1024 skip=2048   count=1024
dd if=ee.bin of=04-env1        bs=1024 skip=3072   count=2560
dd if=ee.bin of=05-env2        bs=1024 skip=5632   count=2560
dd if=ee.bin of=06-kernel      bs=1024 skip=8192   count=32768
dd if=ee.bin of=07-kernel2     bs=1024 skip=40960  count=32768
dd if=ee.bin of=08-storage1    bs=1024 skip=73728  count=28672
dd if=ee.bin of=09-storage2    bs=1024 skip=102400 count=28160
```

These commands are included in the “hg-config.sh” script

Identify Partition Contents - 1

- ”file” command

```
$ file 01-bootloader.bin
u-boot legacy uImage, NAND Flash I, Linux/MIPS …
```

- “strings” command

```
$ strings 04-env1.bin
)bootdelay=1
baudrate=115200
```

- ”hexdump” command

```
$ hexdump -C 01-bootloader.bin
00000000  27 05 19 56 42 ee ee b3  56 29 e9 b9 00 02 25 fc
|'..VB...V)....%.|
00000020  4e 41 4e 44 20 46 6c 61  73 68 20 49 00 00 00 00
|NAND Flash I....|
```

Identify Partition Contents - 2

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- ”binwalk” command

```
$ binwalk 06-kernel.bin
DECIMAL HEXADECIMAL DESCRIPTION
------------------------------------------------------------
0       0x0          uImage header, header size: 64 bytes,
header CRC: 0x2A25C931, created: 2016-01-22 07:35:54, image
size: 19062732 bytes, Data Address: 0x80001000, Entry Point:
0x8000F540, data CRC: 0xA80AE4A8, OS: Linux, CPU: MIPS,
image type: Multi-File Image, compression type: lzma, image
name: "=01.01.02.090”
88      0x58          LZMA compressed data …
1966092 0x1E000C      Squashfs filesystem, little endian,
version 4.0, compression:xz, size: 17096020 bytes, 2776
inodes, blocksize: 131072 bytes, created: 2016-01-22
```

Identify Partition Contents - 3

- **01-bootloader.bin** is the U-Boot bootloader for Linux MIPS
- **02-bootloader2.bin** is unused, it has all bytes at default value (0xff)
- **03-config.bin** probably contains some router configuration
- **04-env1.bin** contains U-Boot environment variables
- **05-env2.bin** only one byte is different from the previous file
- **06-kernel.bin** U-Boot header, Linux kernel, Squashfs file system. It is the boot image

Identify Partition Contents - 3

- **07-kernel2.bin** is exactly, bit by bit, the same content as the previous partition
- **08-storage1.bin** is an empty UBIFS file system (writable, optimized NAND Flash file system)
- **09-storage2.bin** is another UBIFS file system, the one that contains data

The Boot Image

Binwalks helps identifying the Boot Image:

- U-Boot header (64 bytes)
- Images lengths (24 bytes, 8 bytes for first image, 8 bytes for second image and 8 bytes, all "0", as terminator)
- Kernel image, lzma compressed
- Squashfs, root file system image. Can be extracted and analyzed

What was found

- 32 bit MIPS 1004Kc processor, Little Endian
- 128Mb NAND Flash
- Linux version 2.6.36 (October 2010)
- uClibc version 0.9.33.2 (May 2012)
- BusyBox version 1.23.1 (January 2015)
- System built with Buildroot-2015.02

QEMU Emulation

- Choosing Board and CPU emulation in QEMU

```
$ qemu-system-mipsel -M help
Supported machines are:
malta                    MIPS Malta Core LV (default)
mips                     mips r4k platform
mipssim                  MIPS MIPSsim platform
none                     empty machine
```

Choosing a Build System

- **The Yocto Project**
  very powerful, builds a root file system and create a custom Linux distribution. But it has a steep learning curve
- **Buildroot**
  builds the root file system and the kernel, easy and fast to learn, very good user manual
- **Openwrt/LEDE Build System**
  tailored to build a replacement router firmware, documentation scattered in the web site, requires more time to learn compared to Buildroot

Choosing a Buildroot version

- Based on uClibc 0.9.33.2
- With kernel version 2.6.36
- Other libraries with compatible versions
- The version to use is: buildroot-2015.02
- This version doesn't run on Ubuntu 16.04 or 18.04
- Use Debian Wheezy (2013) in a docker Container

The Dockerfile

- The Dockerfile builds a minimal Debian Wheezy container to run Buildroot

```
FROM debian:wheezy
...
RUN apt-get update
RUN apt-get upgrade
RUN apt-get install -y -q \
    bash \
...
RUN mkdir -p         /src/misc
ADD startup.sh       /src/misc/startup.sh
RUN chmod a+x        /src/misc/startup.sh
ENTRYPOINT cd        /src/misc ; ./startup.sh
```

The Docker run command

```
docker run          -h BRHOST                           \
                    --rm                                \
                    -v /tmp/.X11-unix:/tmp/.X11-unix    \
                    -v $HOME:$HOME                      \
                    -e DISPLAY=$GDISPLAY                \
                    -e GUSERNAME=$GUSERNAME             \
                    -e GUID=$GUID                       \
                    -e GGROUP=$GGROUP                   \
                    -e GGID=$GGID                       \
                    -e GHOME=$GHOME                     \
                    -e GSHELL=$SHELL                    \
                    -e GRUNXTERM=$GRUNXTERM             \
                    -e GPWD=$GPWD                       \
                    -it digiampietro/buildroot-armv7
```

Docker run in action

```
valerio@ubuntu-hp:~$ ls -ld br
drwxrwxr-x 6 valerio valerio 4096 ott 26 22:30 br
valerio@ubuntu-hp:~$ grep VERSION /etc/os-release
VERSION="18.04.1 LTS (Bionic Beaver)"
VERSION_ID="18.04"
VERSION_CODENAME=bionic
```

```
valerio@ubuntu-hp:~$ br/..../docker/dockrun.sh
valerio@BRHOST:~$ ls -ld br
drwxrwxr-x 6 valerio valerio 4096 Oct 26 20:30 br
valerio@BRHOST:~$ grep VERSION /etc/os-release
VERSION_ID="7"
VERSION="7 (wheezy)"
```

Buildroot configuration

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- Based on "*qemu_mipsel_malta_defconfig*"
- With the following main modifications
  - Build packages and libraries with debugging symbols, don't strip binaries, no gcc optimization
  - Build gdb, gdbserver, ltrace, strace and cross gdb for the host
  - Include mtd drivers, UBIFS and squashfs file system and tools also for the host
  - Include main libraries used in the router (libcrypt, libsha1, libssh2, openssl, expat, json-c)

Linux kernel configuration

- With the following additional settings
  - Preemptible Kernel
  - NAND Device Support and Support for NAND Flash Simulator
  - UBIFS file system with LZMA compression and squashfs file system

uClibc configuration

- Minor modifications to be compatible with the router's binaries (like linuxthreads etc.)
- To include debugging symbols, uClibc don't obey to the general option included in the Buildroot configuration, has his own flag for this purpose; the problem is that enabling his own flag the compilation gives impossible to fix errors
- in Compiler Warnings add the string "-ggdb", this is the work around to compile the uClibc with debugging symbols

Startup Scripts - 1

- /etc/inittab, snippet:

```
::sysinit:/sbin/sysctl -p
::sysinit:/etc/init.d/rcS
# Put a getty on the serial port
ttyS0::respawn:/sbin/getty -L  ttyS0 115200 vt100
```

- /etc/init.d/rcS

```
for i in /etc/init.d/S??* ;do
     $i start
done
```

- /bin/login

```
$ ls -l bin/login
lrwxrwxrwx 1 root root bin/login -> /bin/shell_auth
```

Startup Scripts - 2

S10mountstorage
S11mountexternalusb
S13portmap
S15create_account.sh
S20urandom
S40network
S49ntp
S59snmpd
S90crond
S99gemtek.sh

Startup Scripts - 3

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S15create_account.sh

- during first boot it copies to /mnt/jffs2/etc
  - /etc/passwd.default
  - /etc/group.default
  - /etc/shadow.default
- /etc/passwd is a link to /mnt/jffs2/etc/passwd
- other files in /etc are links to corresponding files in /mnt/jffs2/etc/

Startup Scripts - 4

S99gemtek.sh

- initialize and starts router specific services:
  - configures specific router hardware
  - inserts Gemtek specific modules into the kernel
  - modifies some kernel parameters
  - executes some interesting programs:

Assignment 2
how to become root analyzing /etc/init.d scripts

- Analyzing the startup scripts in /etc/init.d directory, identify how to get a root shell
- Hint #1: search for a telnetd invocation
- Hint #2: U-Boot env variables are available as bash env variables

Download etc.tar.gz from:
http://va.ler.io/ws
or
http://116.203.78.185

Startup Scripts - 5

S99gemtek.sh: in /etc/profile U-Boot env vars becomes shell vars

```
FACTORY="$factory”
if [ "$FACTORY" -ge "1" ]; then
        DEF_LAN_IP=192.168.15.1
fi
if [ "$FACTORY" ] && [ "$FACTORY" -ge "1" ]; then
        echo "### FACTORY mode ###”
        telnetd -l /bin/sh & \
          udp_sender -udp_sender $DEF_LAN_IP 255.255.255.255 \
          978 "Gemtek Hello" > /dev/null 2>&1 &
          [ "$FACTORY" == "2" ] && fw_setenv factory
        exit 0
fi
```

Startup Scripts - 6

A simple way to become root:

- Enter the U-Boot CLI
- Set the U-Boot var factory at value 2: "setenv factory 2"
- Permanently save the U-Uboot env: "saveenv"
- power down the router, then power up again
- from the PC connect to the router using telnet and you will have a root shell prompt. It is not possible to modify the read only squashfs root file system, but it is possible to explore the system and to modify the content of the UBIFS file system mounted under /mnt/jffs2

Startup Scripts - 7

S99gemtek.sh: at the end it executes the 2 processes managing the router

```
proc_mon &
msg_center &
```

- **proc_mon** monitors some processes and restarts them if needed
- **msg_center** is the process that manages the router doing practically anything. It is really really interesting to analyze the embedded strings in msg_center

Reverse engineering shell_auth

shell_auth is a stripped binary, but calls library functions. We put breakpoints on these calls in the emulation environment

```
$ mipsel-linux-readelf --sym -D shell_auth
Symbol table for image:
Num Buc Value    Size Type    Bind   Vis      Ndx Name
 36   0: 00401ba0    0 FUNC    GLOBAL DEFAULT UND OPENSSL_add_all_algo…
 26   1: 00401c30    0 FUNC    GLOBAL DEFAULT UND RSA_public_encrypt
 39   1: 00401b70    0 FUNC    GLOBAL DEFAULT UND BIO_set_flags
 44   1: 00000000    0 NOTYPE  WEAK   DEFAULT UND _Jv_RegisterClasses
 48   1: 00401af0    0 FUNC    GLOBAL DEFAULT UND strcmp
 14   2: 00401ce0    0 FUNC    GLOBAL DEFAULT UND memcpy
  9   3: 00412040    0 OBJECT GLOBAL DEFAULT  19 __RLD_MAP
 29   4: 00000000    0 FUNC    WEAK   DEFAULT UND __register_frame_info
 42   4: 00401b40    0 FUNC    GLOBAL DEFAULT UND strrchr
 43   4: 00401b30    0 FUNC    GLOBAL DEFAULT UND RSA_private_decrypt
  1   4: 004018cc  356 FUNC    GLOBAL DEFAULT   9 main
 33   9: 00401bd0    0 FUNC    GLOBAL DEFAULT UND BN_bin2bn
```

Running shell_auth in GDB - 1

Start gdb server in the emulation environment

```
# gdbserver :9000 ./shell_auth
  Process ./shell_auth created; pid = 840

  Listening on port 9000
```

Start gdb in the host machine

```
$ arm-linux-gdb --ex="target remote :9000" \
               --ex="set sysroot $SYSROOT"\
               --ex="directory $MYDIR"    \
               --ex="directory $TOOLBIN"  \
                 -x shell_auth.gdb
```

Running shell_auth in GDB - 2

1. it calls *RSA_new* to allocate a public/private key: *generated_rsa*
2. it calls *RSA_new* to allocate a public/private key: *eprom_rsa*
3. it calls *RSA_generate_key_ex* to generate a new RSA public/private key at address *generated_rsa*
4. the modulus of the *generated-rsa* is serialized with *BN_bn2bin* and stored at address *generated-rsa.modulus*
5. a modulus, stored inside the shell_auth binary, is copied into the *eprom-rsa*, initializing only the public key

Running shell_auth in GDB - 3

6. *RSA_public_encrypt* is used to encrypt the *generated-rsa.modulus* with the public key *eprom-rsa*
7. the encrypted *generated-rsa.modulus* is base64 encoded and printed as the challenge string
8. the login prompt does expect a base64 string of 128 original bytes. If shorter login is aborted writing "Fail!”
9. if the login input has the correct length, it is base64 decoded and decrypted with *RSA_private_decrypt* using the private key *generated-rsa*

shell_auth summary

1. the challenge code is the public key to use to encrypt the login user's password
2. the challenge code is encrypted with the Gemtek public key stored inside the shell_auth binary and base64 encoded
3. to decrypt the challenge code we need the Gemtek private key
4. we don't know the Gemtek private key, this means that there is no way to successfully login with shell_auth
5. we can defeat this protection modifying the firmware replacing shell_auth with standard /bin/login

Analyzing msg_center


```
$ strings msg_center | grep assist
/bin/assistant -p hO2PHGNmaX0Ww!v0eqD8 -w xvoip_password_1
               -t xvoip_plaintext_pw_1
/bin/assistant -p hO2PHGNmaX0Ww!v0eqD8 -w xvoip_password_2
               -t xvoip_plaintext_pw_2
/bin/assistant -p hO2PHGNmaX0Ww!v0eqD8 -w iad_xvoip_password_1
               -t iad_xvoip_plaintext_pw_1
/bin/assistant -p hO2PHGNmaX0Ww!v0eqD8 -w iad_xvoip_password_2
               -t iad_xvoip_plaintext_pw_2
/bin/assistant -p hO2PHGNmaX0Ww!v0eqD8 -g
     assistant -p hO2PHGNmaX0Ww!v0eqD8
               -w wifi -h "$serial" -s %s 2> dev/null |
                cut -c1-8 | tr 'A-Z' 'a-z'
```

Analyzing ”assistant”

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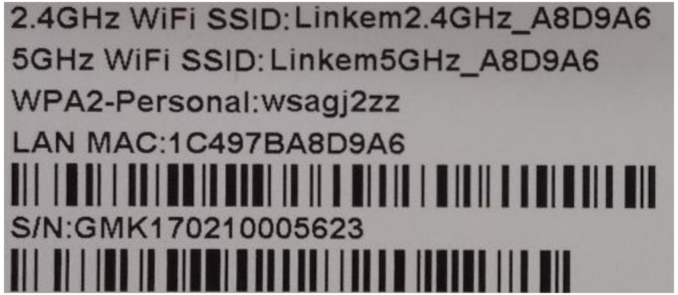


SSID: Linkem2.4GHz_**A8D9A6**

S/N: GMK**170210**005623

WPA2-Personal: wsagj2zz

```
# ./assistant -p hO2PHGNmaX0Ww!v0eqD8 \
               -w wifi -h "GMK170210005623" -s A8D9A6
WSAgj2ZZ

# ./assistant -p hO2PHGNmaX0Ww!v0eqD8 \
               -w wifi -h "GMK170210005623" -s A8D9A6 \
               2> /dev/null | cut -c1-8 | tr 'A-Z' 'a-z’
wsagj2zz
```

Reverse engineering “assistant”

1. it calculates the SHA1 digest for the router's serial number

```
Breakpoint 36, SHA1 (d=0x7fff63ec "GMK170210005623", n=15,
md=0x7fff618c "") at sha1_one.c:70. SHA1 (20 bytes):
c4 0d e4 96 16 20 cf bc c6 c9 05 66 54 4a 8f 8f 2a 59 25 d8
```

3. A8D9A6 is used to pickup 6 bytes from the SHA1

   ‘A’-’0’=17; ‘8’-’0’=8; ‘D’-’0’=20; ‘9’-’0’=9; ‘A’-’0’=17; ‘6’-’0’=6

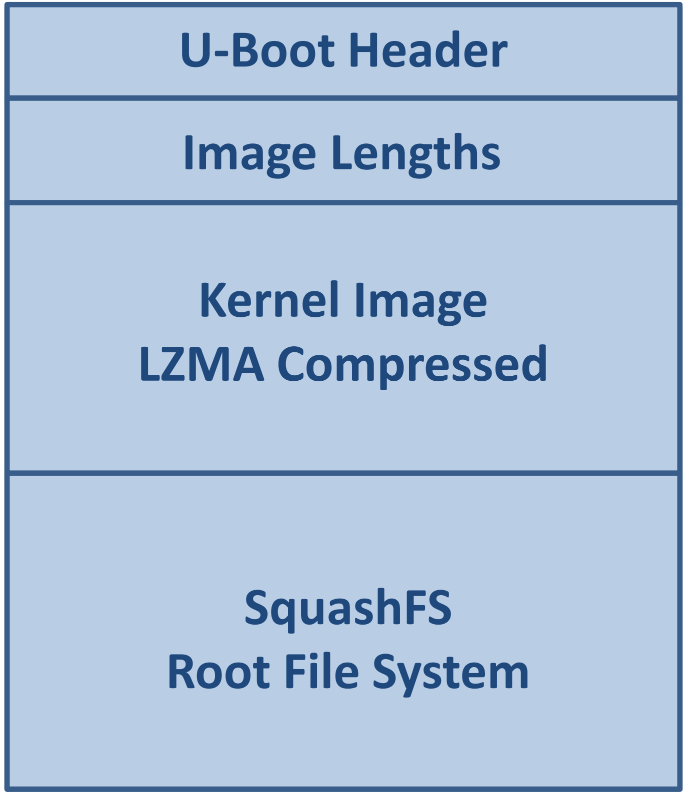
```
Bin password: 59 20 20 8f 66 59
```

5. the bin password is base64 encoded and transformed in lowercase

```
$ echo "5920 208f 6659" | xxd -r -p | base64
WSAgj2ZZ
wsagj2zz (lowercase version)
```

Firmware modification kit - 1

Kernel/Boot Partition



Firmware Modification Kit - 2

- Extract the squashfs root file system, modify it
- Create the new root file system image
- Reassemble the firmware file putting together all the pieces using the ”dd” command
- Recalculate header checksums and image lengths
- The new kernel/boot image is ready
- Script the process and create the firmware mod kit

Flash the new firmware

- With file system analysis we discover the command

```
fwupgrade mtdn boot-image-file [startaddress] [endaddress]
```

- Copy the new kernel/boot image into the device

```
# cd /tmp
# tftp -r kernel.bin -l kernel.bin -g 192.168.1.100
kernel.bin  |*************************| 32768k  0:00:00 ETA
```

- Flash the new image

```
# echo $mtddevnum
6
# fwupgrade mtd6 kernel.bin
Erasing 128 Kibyte @ 2000000 - 100% complete.
# reboot
```

Summary

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- Reverse engineering can be really challenging
- Clearly define the limited scope of the project
- Start gathering information following the easiest path first
- If some information is missing or difficult to get move forward, go back only if absolutely needed
- Search on Internet for known vulnerabilities
- Select to hack processes running as root and with a large attack surface

Useful Links & Documentation - 1

GitHub repositories related to the Home Router Example

- **Hacking-gemtek**: a complete reverse engineering project on the home router example: *https://github.com/digiampietro/hacking-gemtek*
- **Adbtools2**, Tools for hacking another ADB Epicentro routers, including firmware modification: *https://github.com/digiampietro/adbtools2*
- **Buildroot-armv7**: a set of scripts, configuration files and Buildroot external tree to setup a Qemu emulation environment to run and reverse engineer the Netgear DVA 5592 executables: *https://github.com/digiampietro/buildroot-armv7*

Reverse engineering and physical disassembly

- Introduction to reverse engineering, Mike Anderson, Embedded Linux Conference 2018, slides and videos:
  https://elinux.org/images/c/c5/IntroductionToReverseEngineering_Anderson.pdf
  https://www.youtube.com/watch?v=7v7UaMsgg_c

Useful Links & Documentation - 2

Recommended Books

- *Chris Simmonds* - Mastering Embedded Linux Programming - Second Edition - *Packt Publishing 2017*
- *Norman Matloff , Peter Jay Salzman* - The Art of Debugging with GDB , DDD and Eclipse - *NO STARCH PRESS 2008*

Hardware tools

- Bus Pirate: http://dangerousprototypes.com/docs/Bus_Pirate
- Jtagulator: http://www.grandideastudio.com/jtagulator/
- J-Link debug probes: https://www.segger.com/products/debug-probes/j-link/

JTAG and UART interfaces

- Popular pinouts: http://www.jtagtest.com/pinouts/

Useful Links & Documentation - 3

Software

- Buildroot: https://buildroot.org/
- Putty terminal emulator: *https://www.putty.org/*
- OpenOCD (Open On-Chip Debugger) provides debugging, in-system programming and boundary-scan testing for embedded target devices: *http://openocd.org/*
- Wireshark, network protocol analyzer: *https://www.wireshark.org/*
- Binwalk, firmware analysis tool: *https://github.com/ReFirmLabs/binwalk*
- Jefferson, JFFS2 filesystem extraction tool: *https://github.com/sviehb/jefferson*

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Question Time

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Thank You

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