Reverse-enigneering embedded MIPS devices

Case study: Draytek SOHO routers

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Reverse-enigneering embedded MIPS devices

- Embedded systems: overview
- Firmware research
- MIPS: Introduction
- MIPS: Reversing and exploitation
- Case study: DrayTek SOHO routers

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Embedded systems: overview

- Everywhere: mobile, media, CPE, …
- High level of integration: mostly SoC
- Compact size, low power consumption
- ARM, MIPS, xScale, …
- A real challenge for a reverser
  - Variety of models
  - Variety of architectures, conventions and APIs
  - Lack of information

Embedded systems: overview

Why ever reverse a MIPS box ?

- Ubiquitous devices – especially network & CPE
- A well-known RISC platform
- Surprisingly, a little of security research:

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Firmware research

Firmware – how to get it?

- Download from device …
  - JTAG
  - Serial / UART console / other ports
  - read EEPROM directly, etc.
- … or simply find a firmware upgrade
  - Single file, several MB's in size
  - Encrypted / compressed

Firmware research

Typical firmware binary:

- Bootloader
- Code
- Filesystem image

How to extract them?

- Manual review
- Tools

Firmware research :: Tools

- Signature search
  - `binwalk`
  - `signsrch, offzip`
  - `trid`
- Scriptable hex editor
  - `<Your favourite here>`
- A set of archivers / unpackers
  - `<Your favourite here>`
- `%script_lang_name%`

Firmware research :: Manual review

- Sequences of `0x00`'s and `0xFF`'s
- First byte/word may be block size
- Last byte/word may be block checksum
- Magic signatures
- Text strings
  - Extract, sort, guess and google
- Entropy

Firmware research :: Manual review

- Filesystem extraction
  - Use binwalk
  - Or look for magic headers
    - JFFS2 = `85 19` (for FS nodes)
    - cramfs = `45 3D CD 28`
    - YAFFS = `03 00 00 00 01 00 00 00 FF FF`
    - SquashFS = `"hsqs"`
    - VFAT, etc. …

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Embedded systems: overview

Firmware research

MIPS: Introduction

MIPS: Reversing and exploitation

Case study: DrayTek SOHO routers

MIPS: Introduction

- RISC ISA (instruction set architecture)
- Fixed 4-byte length instructions
- 32-bit and 64-bit
- Both big-endian and little-endian
- Popular and even more promising with multi-core Loongson series from China

MIPS: registers

Name	Number	Purpose
$zero	$0	Const = 0
$at	$1	Temporary
$v0–$v1	$2-$3	Return values
$a0–$a3	$4-$7	Function args
$t0–$t7	$8-$15	Temporary
$s0–$s7	$16-$23	Saved values
$t8–$t9	$24-$25	Temporary
$k0–$k1	$26-$27	Reserved for OS kernel
$gp	$28	Global pointer
$sp	$29	Stack pointer
$fp	$30	Frame pointer
$ra	$31	Return address

MIPS: delay slot

- MIPS is a pipelined architecture

IF	ID	EX	MEM	WB				
	IF	ID	EX	MEM	WB			
		IF	ID	EX	MEM	WB		
			IF	ID	EX	MEM	WB	
				IF	ID	EX	MEM	WB

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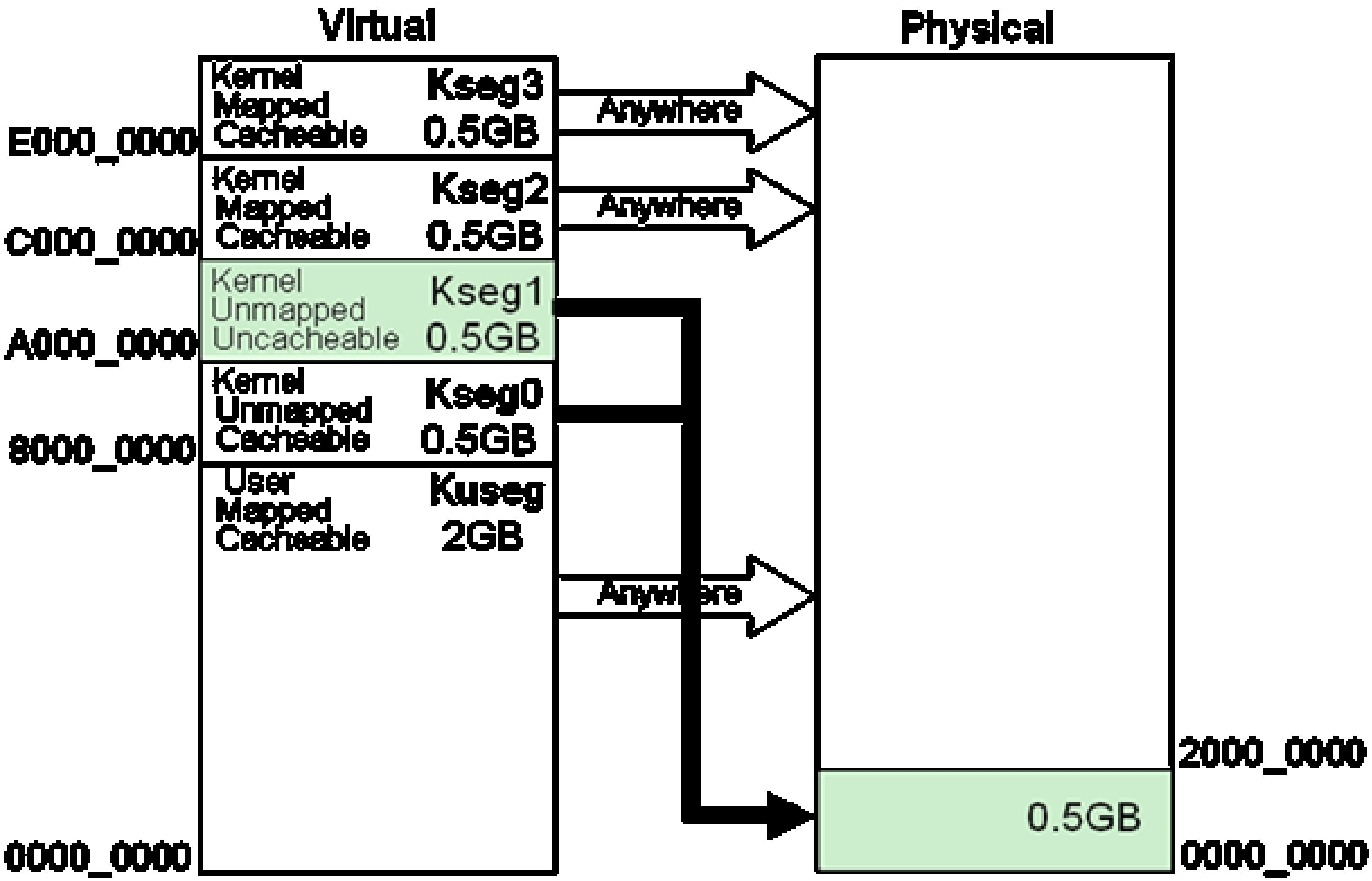
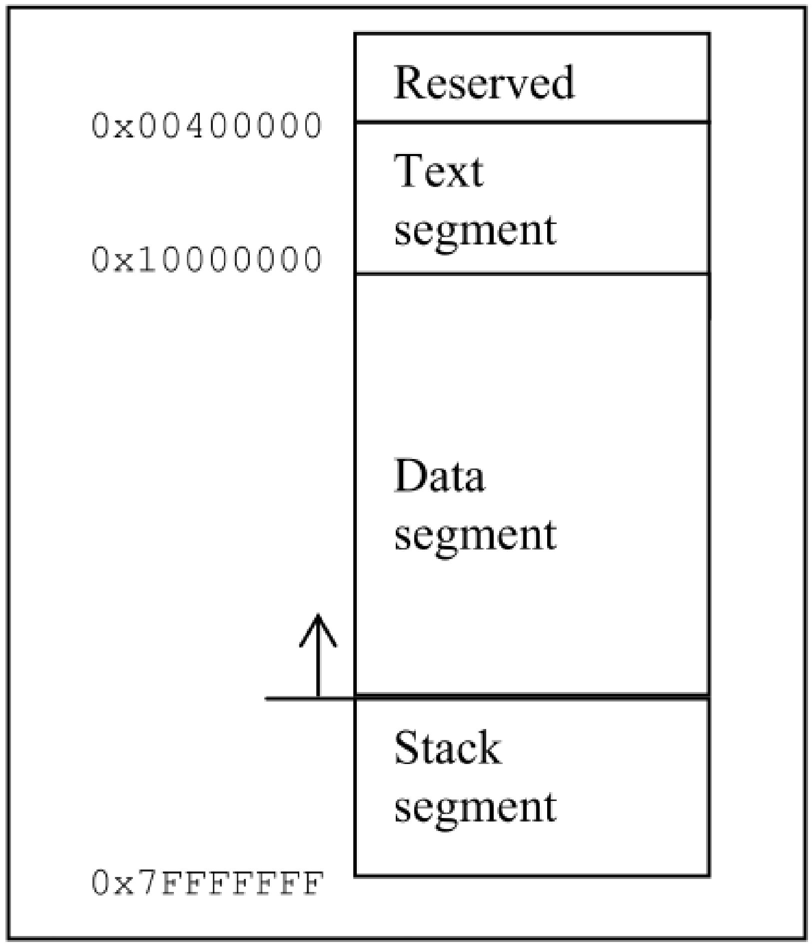
- So not all instructions are safe to be executed right after others
  - branches & jumps (**`bne beq j jr jal`**)
  - Loads (**`lb lw ld`**)

MIPS: memory layout



MIPS: memory layout



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MIPS: Reversing and exploitation

- objdump / disasmips / radare
- IDA
  - IDAPython
  - QEMU-MIPS
- MIPS emulator
  - SPIM
  - OVPsim

MIPS: Reversing and exploitation

- Delay slots

```
# =============== S U B R O U T I N E =======================================


schedule_insns_bug:
                lw      $v0, dword_80559A10  # Load Word
                addiu   $sp, -0x10          # Add Immediate Unsigned
                sltiu   $v0, 1              # Set on Less Than Immediate Unsigned
                jr      $ra                 # Jump Register
                addiu   $sp, 0x10           # Add Immediate Unsigned
# End of function schedule_insns_bug
```

MIPS: Reversing and exploitation

- Finding code patterns
  - 03 E0 00 08 (jr $ra -- return)
  - 0C xx xx xx (jal)
  - 3C xx xx xx (load – lui, la, ...)
  - 1x xx xx xx (branches)

```
                alloc_etherdev:                                  # CODE XREF: RT28xx_MBSS_I
                                                                 # RT28xx_WDS_Init:loc_801(

                var_8           = -8

27 BD FF E8                     addiu   $sp, -0x18               # Add Immediate Unsigned
3C 05 80 60+                    la      $a1, aEthD               # "eth%d"
3C 06 80 2F+                    la      $a2, ether_setup          # Load Address
AF BF 00 10                     sw      $ra, 0x18+var_8($sp)     # Store Word
0C 0B D8 B8                     jal     alloc_netdev             # Jump And Link
00 00 00 00                     nop
8F BF 00 10                     lw      $ra, 0x18+var_8($sp)     # Load Word
03 E0 00 08                     jr      $ra                      # Jump Register
27 BD 00 18                     addiu   $sp, 0x18                # Add Immediate Unsigned
                 # End of function alloc_etherdev
```

MIPS: Reversing and exploitation

- Finding more details about the target system is a key to understanding kernel procedures

```
14000000    14000FFF     external bus general purpose i/o
18000300    180003FF     general purpose timer
1E100400    1E1007FF     first serial port
...
1E103100    1E1031FF     hardware crypto
1E104100    1E1041FF     dma controller
1E105300    1E1053FF     external bus controller
1E105400    1E1057FF     PCI bus controller
1E116000    1E117000     DSL interface
1E180000    1E1BFFFF     ethernet controller
1F101000    1F101FFF     external interrupt controller
...
1F203000    1F203FFF     reset controller
1F880200    1F8802FF     interrupt controller
1F8803F0    1F8803FF     watchdog timer
```

MIPS: Reversing and exploitation

- Basic buffer overflow
  - Owerwrite the old $ra stored on stack
  - ret2libc
  - …

	addr	Stack contents
new $sp→	X-28	allocated by the compiler
	X-24	allocated by the compiler
	X-20	local_buf[0] … local_buf[3]
	X-16	local_buf[4] … local_buf[7]
	X-12	local_buf[8], local_buf[9] …
	X-8	Global pointer ($gp) from main()
	X-4	Return address ($ra) back into main()
old $sp→	X	…

MIPS: Reversing and exploitation

- Exploitation is more difficult than on x86 and ARM
  - Fixed-length instructions with a lot of ull bytes
  - Word-aligned instructions (32 bit)
  - Word-aligned memory words (32 bit)
  - I-Cache vs. D-Cache (exploit has no effect, data & code is read & executed from cache)
- But protection techniques are still rather new
  - ASLR (MIPS Linux > 2.6.23)
  - Stack canaries (GCC > 4.5)
  - W ^ X not standardized and rarely implemented

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Case study: DrayTek SOHO routers

Case study: DrayTek SOHO routers

- DrayTek Vigor V2xxx series – network devices
  - Over 35 models, widely deployed by ISP's over Australia, Germany, UK
    - Routers
    - ADSL-modems
    - CPE & combo devices (dual wan + VoIP + …)
- MIPS and ARM platforms
  - POI: Infineon Danube-S (MIPS, dual-core, HW crypto)
- Proprietary closed-source OS: DrayOS
  - Single static non-relocatable binary
  - Capable of loading Linux drivers

Case study: DrayTek SOHO routers

- Router Web UI allows to download obviously obfuscated binary config for further reloading
- Firmware upgrades available from vendor, but they are compressed using unknown algorithm
- Rumours are that a master key based on MAC address exist

Case study: DrayTek SOHO routers

Research steps.

1. Config file – decrypt
2. UART console and debug menu
    1. Firmware dumped through UART hexdump 100 bytes at a time ☺
3. Firmware reversing
4. Config file – decompress
5. Firmware – decompress
6. Filesystem – decompress & extract
7. Master password generation algorithm discovered

Config file

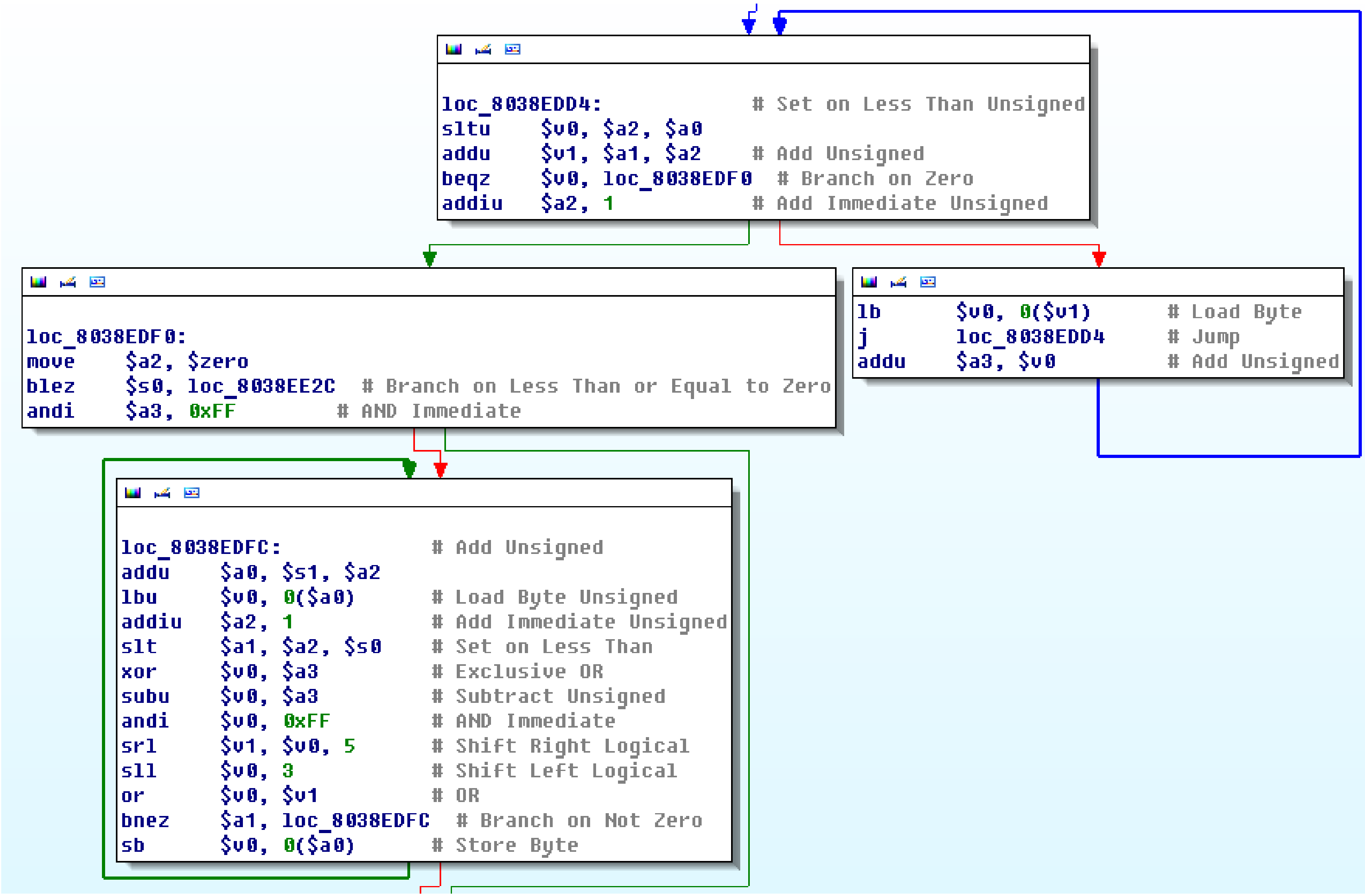
1. A way to get encrypted and unencrypted configs simultaneously was discovered
   1. Immediate result – a cipher used is definitely in ECB mode, bytewise substitution table is made
   2. Substitution table shows strong symmetry, the cipher is extremely weak
2. Now try to uncompress – firmware research suggests to try LZO algorithm
3. Success!
4. Passwords offsets are found to be constant in the config file

Config file

```
struct CFG_HEADER {
    uint32  file_size;         // Total file size
    byte    magic0 [8];        //
    uint16  modelid;           // Big-endian BCD model number, e.g. \x27\x10 = 2710
    byte    signature1 [18];   //
    uint32  magic1;            //
    uint32  cfg_size;          // Config data size, without header and trailing bytes
    byte    flags [8];         //
    uint32  v2k_checksum;      // V2kCheckSum checksum of unencrypted data
    byte    reserved [204];    //
} ;
```

- The config file content itself is a slice of memory

Config file


loc_8038EDD4: # Set on Less Than Unsigned
sltu $v0, $a2, $a0
addu $v1, $a1, $a2 # Add Unsigned
beqz $v0, loc_8038EDF0 # Branch on Zero
addiu $a2, 1 # Add Immediate Unsigned
loc_8038EDF0:
move $a2, $zero
blez $s0, loc_8038EE2C # Branch on Less Than or Equal to Zero
andi $a3, 0xFF # AND Immediate
lb $v0, 0($v1) # Load Byte
j loc_8038EDD4 # Jump
addu $a3, $v0 # Add Unsigned
loc_8038EDFC: # Add Unsigned
addu $a0, $s1, $a2
lbu $v0, 0($a0) # Load Byte Unsigned
addiu $a2, 1 # Add Immediate Unsigned
slt $a1, $a2, $s0 # Set on Less Than
xor $v0, $a3 # Exclusive OR
subu $v0, $a3 # Subtract Unsigned
andi $v0, 0xFF # AND Immediate
srl $v1, $v0, 5 # Shift Right Logical
sll $v0, 3 # Shift Left Logical
or $v0, $v1 # OR
bnez $a1, loc_8038EDFC # Branch on Not Zero
sb $v0, 0($a0) # Store Byte

Config file

```
def make_key(modelstr):               # Make a key out of model string
    sum = 0                           #
    for c in modelstr:                # sum character codes of the string
        sum += ord(c)                 #
    return (0xFF & sum)               # take only lower byte of the sum (= mod 256)

def enc(c, key):                      # Encrypt a byte of data
    c ^= key                          # XOR a byte with a key
    c -= key                          # Subtract a key from the previous step result
    c = 0xFF & (c >> 5 | c << 3)      # Swap 3 leftmost bits and 5 rightmost bits
    return c                          #
```

Firmware file

```
[4 bytes   ] = the size of (loader code + main code).
[4 bytes   ] = currently unknown purpose
[248 bytes ] = rest of header, zeroes
[varies    ] = firmware loader code (uncompressed)
[8 bytes   ] = loader end signature - 8 bytes ending
  in A55AA55A, XXA5A5A55AA55A or XX5A5AA55AA55A

[4 bytes   ] = compressed code size
[varies    ] = compressed firmware code
[4 bytes   ] = compressed filesystem image total size
[4 bytes   ] = compressed filesystem image data size
[varies    ] = compressed filesystem image
[varies    ] = garbage or padding at the end
```

Filesystem

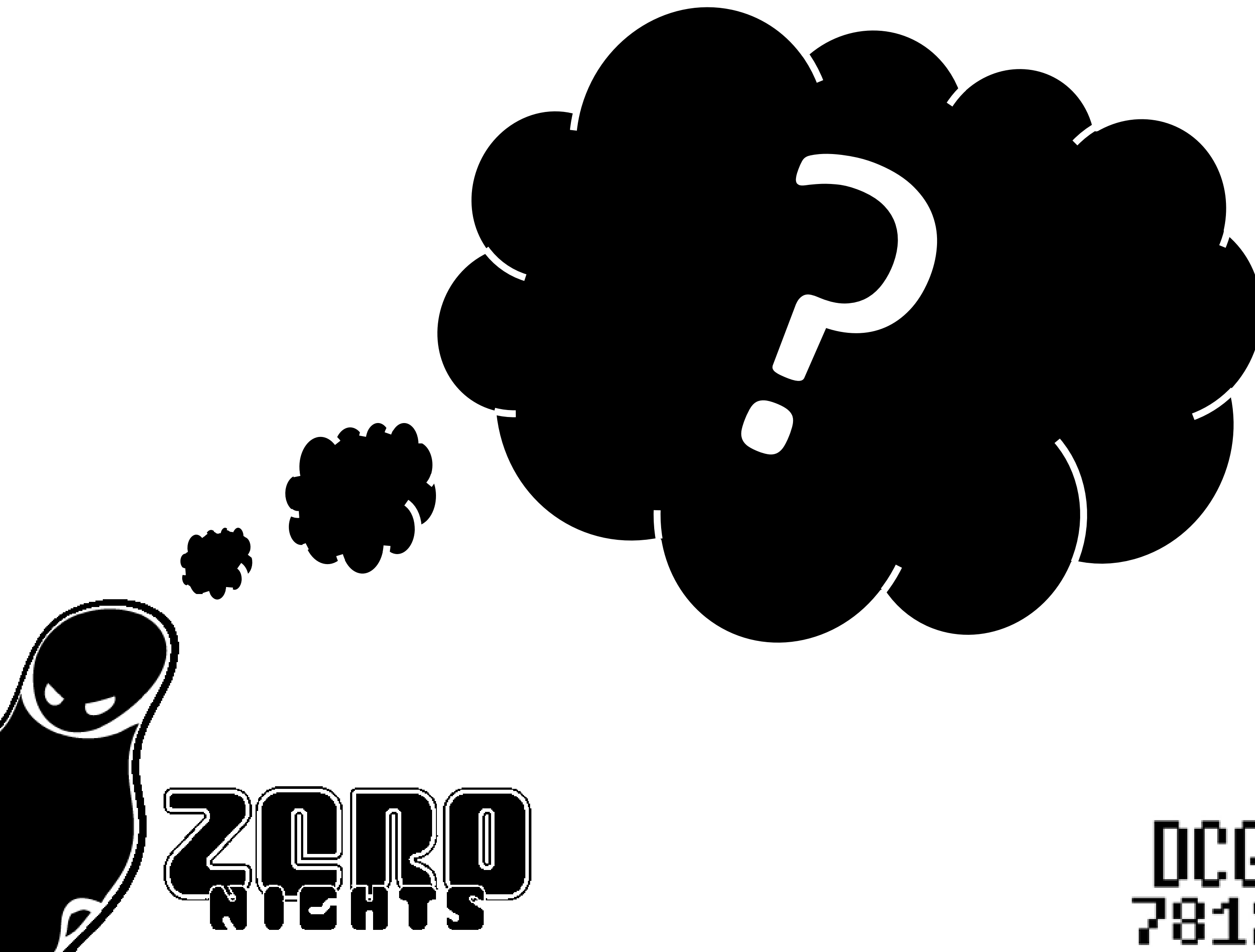
```
[16 bytes   ] = filesystem header block
[N*44 bytes ] = file nodes block, 44 bytes in each node
[N*variable ] = compressed files block, all files are simply
   concatenated, no padding or alignment

struct FS_HEAD {
    char magic  [8];   // "PFS/1.0\x00"
    byte unused [6];   // zeroes
    uint16 num_files;  // number of files
}
struct FS_ENTRY {
    char fname [32];   // file name, right zero-padded
    uint32 hash;       // some hash, not researched yet
    uint32 offset;     // offset from the beginning of common compressed
   file block
    uint32 size;       // compressed file size
}
```

Master key

- Derived from local interface MAC address
- 8-byte, alternating case letters , e.g. 'AaBbCcDd'
- Login allowed only from local addresses to FTP
- The same algorithm for all V2xxx devices (from 2002 to 2012)
  - Compute a simple polynom over MAC address bytes
  - Divide by 26 and map result to reordered alphabet
  - Repeat until all chars filled

Strange findings

	Type	String
	C	Whether this will happen ???? I hope it would never happen ---- Fanny\r\n
	C	====>Please Tell Fanny : When will this happen.....???????\r\n
	C	D-Channel pkt size > %d (Exceeds D-Channel buffer size : %d)\r\n



ZERO NIGHTS

DCG 7812

Keywords & links

binwalk , signsrch, SPIM, disasmips, OVPsim, QEMU-mips

MIPS linux wiki www.linux-mips.org

Case study reference:

draytools github.com/ammonium