Packin' the PMK

Of the robustness of WPA/WPA2 authentication

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Special guest
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BA-Con - September 30th - October 1st 2008
http://ba-con.com.ar/

Agenda

1. WPA/WPA2 authentication
2. WPA-PSK assessment
    - How does that work ?
    - Theoritical attack cost
    - Implementation comparisons
    - Passphrase strength assessment
    - Limits of practical attacks
3. WPA-EAP thoughts
    - EAP authentication
    - Pwning the Master Key
    - Practical considerations
4. Conclusion

Introduction

Wi-Fi security...

- WEP is crippled and broken
- WPA came up to replace it
- Now, we have WPA2

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Questions

- What are WPA and WPA2 good at ?
- How long will they stand ?

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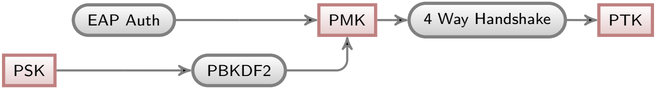
Authentication modes

- Preshared secret (PSK)
- EAP



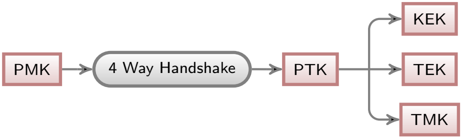
Key hierarchy

- Authentication leads to Master Key (MK)
- Pairwise Master Key (PMK) derived from MK

One key to rule them all...

From MK come all further keys

- Pairwise Master Key
- Key exchange keys
- Encryption keys
- Authentication keys if applicable



Conclusion

Owning the Master Key == Owning everything else

The Preshared Key option

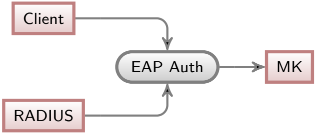
- MK is your PSK
- PMK is derived from MK

PSK situation

Owning the PSK == Owning MK

The EAP option

- Authentication between client and RADIUS
- MK derived from authentication



- MK pushed to AP by RADIUS

EAP situation

Owning client+RADIUS == Owning MK

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Calculating the PMK

The master key (MK)

- it is your secret key, password or passphrase
- 8 to 63 printable ASCII characters (between code 32 and 126)

The pairwise master key (PMK)

- derives from the master key and AP data using the PBKDF2 function
- the derivation function is time consuming

The attack

Retrieving the relevant data

- it must be captured during the handshake
- it is possible to force this handshake
- only works for a single SSID

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Testing a master key

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2. compute the PTK (four HMAC-SHA1 calls using PMK and nonces)

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Testing a master key

1. for every potential MK, compute the corresponding PMK
2. compute the PTK (four HMAC-SHA1 calls using PMK and nonces)
3. finally, get the MIC (one HMAC-SHA1 call) and compare it with the captured handshake

The PBKDF2 function

Algorithm of PBKDF2

```
x1 = HMAC_SHA1(MK, SSID + '\1');
x2 = HMAC_SHA1(MK, SSID + '\2');
for(i=1;i<4096;i++) {
        x1 = HMAC_SHA1(MK, x1);
        x2 = HMAC_SHA1(MK, x2);
}
return x1 + x2;
```

Cost

- 8192 calls to HMAC-SHA1

The HMAC-SHA1 function

Algorithm for HMAC(secret, value)

put `secret` in two 64 bytes buffers, `Bi` and `Bo`, padding with zeroes

```
Bi
secret00000000000000000000000000
00000000000000000000000000000000

Bo
secret00000000000000000000000000
00000000000000000000000000000000
```

The HMAC-SHA1 function

Algorithm for HMAC(secret, value)

- `XOR Bi with 0x36`
- `XOR Bo with 0x5c`

```
Bi
ESUDSB66666666666666666666666666
66666666666666666666666666666666

Bo
/9?.9(\\\\\\\\\\\\\\\\\\\\\\\\\\
\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\
```

The HMAC-SHA1 function

Algorithm for HMAC(secret, value)

`append value to Bi`

Bi

```
ESUDSB66666666666666666666666666666
66666666666666666666666666666value
```

The HMAC-SHA1 function

Algorithm for HMAC(secret, value)

append `SHA1(Bi)` to `Bo`

Bo

```
/9?.9(\\\\\\\\\\\\\\\\\\\\\\\\\\
\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\
e7de45e0b885228e9a48a9add37b504eba7fd3c4
```

The HMAC-SHA1 function

Algorithm for HMAC(secret, value)

get `SHA1(Bo)`

`330b72d384df41adf440e1d8aeb543ab73eecb8a`

Summary

$$HMAC\_SHA1(s,v) = SHA1((s \oplus 0x5c)||SHA1((s \oplus 0x36)||v))$$

The SHA1 function

Description

- it is a cryptographic hash function
- works on 64 bytes blocks by padding user inputs
- produces a 20 bytes digest
- the main part of this function is called "BODY"
- other parts have an amortized cost of zero

The HMAC trick

Reminder

- we want `SHA1(Bo || SHA1(Bi || value))`

What will be computed

- `BODY(secret ^ 0x5c)`
- `BODY(value + padding)`
- ⇒ `hash1`
- `BODY(secret ^ 0x36)`
- `BODY(hash1 + padding)`
- ⇒ result

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- if the secret is constant ...
- ... two `BODY` calls could be cached

The BODY function – initialization

Algorithm

```
unsigned int K[80];
memcpy(K, input, 64);
a = ctx[0]; b = ctx[1]; c = ctx[2];
d = ctx[3]; e = ctx[4];
```

Operation count

- 32 bits memory assignments : 22

The BODY function – input expansion

Expand the input

```
K[i] = K[i-3] ^ K[i-8] ^
     K[i-14] ^ K[i-16];
K[i] = rotate_left(K[i],1);
```

Operation count

- 32 bits memory assignment : 1
- elementary operations : 4
- done 64 times

The BODY function – rounds

Algorithm

```
STEP(v,w,x,y,z,m,c):
    z += F(w,x,y) + c + K[m];
    z += rotate_left(v,1);
    w = rotate_left(w,30);
```

Operation count

- 32 bits memory assignments : 2
- elementary operations : 5 + cost of F
- 4 rounds of 20 steps
- the average F cost is 3.75 operations

The BODY function – ending

Algorithm

```
a += ctx[0]; b += ctx[1]; c += ctx[2];
d += ctx[3]; e += ctx[4];
```

Operation count

- 32 bits memory assignments : 5
- elementary operations : 5

The BODY function – summary

Elementary operations count

- initialization : 0
- input expansion : 4 times 64
- rounds : 8.75 times 80
- ending : 5
- total : 961

Comparison with MD5

- MD5 BODY function : 496
- if cracking a single MD5 : 317

The PBKDF2 function cost

Elementary operations count

- it requires 8192 HMAC-SHA1 calls using the same secrets
- that is, $2 + 8192 * 2$ calls to SHA1
- that means 15.7M elementary operations

The PBKDF2 function theoritical speed

Hypothesis : perfect processors

- memory fetch/stores are free
- no penalties

Speeds

- for a perfect SSE2 implementation running at 3Ghz on a single x86 core, about 500 checks/s
- for a perfect native CELL (PS3, 7 SPUs) implementation, about 2,840 checks/s
- for a perfect Linux CELL implementation, about 2,440 checks/s

Real world implementations

Aircrack

- 650 checks/s on Xeon E5405 (4x2Ghz)
- 650 checks/s on Opteron 2216 (4x2.4Ghz)
- "pipe multithreading", fails on AMD

Pico Computing products

- on a LX25 FPGA, 430 checks/s
- on a FX60 FPGA, 1,000 checks/s

Pyrit (GPU Project)

- around 6,000 checks/s on Tesla C870

Other cracking methods

WPA-PSK "rainbow tables"

- really PMK lookup tables
- precomputation of 1,000,000 passwords for 1000 SSIDs

Jason Crawford CELL implementation

- *"Lockheed Breaks WPA-Encrypted Wireless Network With 8 Clustered Sony PlayStations"*
- why did I bother, it is already broken :/
- unknown performance

Implementation on the cell architecture

CELL benchmark

- not a real cracker, just a bench
- under Linux, so only 6 SPUs are available
- pipeline filled by cracking 16 passwords at the same time

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Result

- 2,300 checks/s
- close to theoritical 2,400 checks/s
- expected on CELL

My implementation

NVidia CUDA cracker

- (almost) full fledged cracker, needs input from a modified aircrack-ng
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Result

- 4,400 checks/s on a 8800 gts
- 12,000 checks/s on a gtx280
- might not be too hard to do better
- roughly equivalent to Pyrit

The best bang for the buck

Raw cost comparisons

Type	checks/s	cost	checks/s/$
LX25	430	385$	1.1
Q6600	800*	190$	4.2
Q9550	900*	325$	2.77
CELL	2300	400$	5.75
gtx280	12,000	440$	27.3
gtx260	9200*	300$	30.6

But . . .

- speeds marked with a * are not actual benchmarks, but interpolated results
- the CELL costs of 400$ is for a *whole PlayStation*

Password strength assessment function

A function F gives the strength s of password p : $F(p) = s$.

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Desirable properties

1. compute $F(p)$ effectively for any given p
2. for a given s_{max}, enumerate and generate all passwords $\{p_0, p_1, \ldots p_n\}$ where $F(p_i) < s_{max}, 1 \leq i \leq n$
3. generate the set $\{p_a, p_{a+1}, \ldots p_b\}$ where $F(p_i) < s_{max}, a \leq i \leq b$ without generating $\{p_0, \ldots p_{a-1}\}$
4. assess the strength on a detailled scale

Well known methods

Dictionnary checks

it is weak if it is in a dictionnary

⇒ limited to "known" passwords

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Cracking tests

it is weak if it is cracked in less than 4 hours with john on my computer
⇒ requires computing ressources compatible with the risk analysis

A better method

Markov chains

- the conditional probability distribution of letter L_n in a password is a function of the previous letter, L_{n-1}, written $P(L_n|L_{n-1})$
- for example, $P(sun) = P(s).P(u|s).P(n|u)$
- to keep friendly numbers, $P'(x) = -10.log(P(x))$
- $P'(sun) = P'(s) + P'(u|s) + P'(n|u)$

In practice

It works well

- has all the desired properties
- cracks more effectively than *john -inc* (in my tests !)
- a patch exists for *john*

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Sample strength

- "chall", strength 100
- "chando33", strength 200
- "chaneoH0", strength 300
- "chanlLr%", strength 400
- "chanereaAiO4", strength 500
- "% !", strength 1097

Hypothesis

Attacker strength

Attacker	Available time	Ressources (GPUs)
Wardriver	15 minutes	1
Individual	7 days	2
Large organisation	1 year	1024

Defender strength

- worst case scenario : mac user :)
- password is 12 characters or less

Not so good passwords

Statistics source

- an Apple themed forum that got owned
- clear text passwords published on 4chan

Passwords strength

- 628,753 passwords
- mean strength : 245
- median strength : 197
- most common passwords "base" : password, qwerty, apple, letmein

Strength of crackable passwords

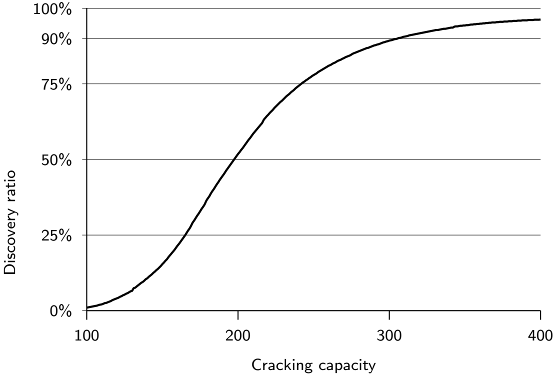
Now

- wardriver : 7.2M, markov strength of 169
- individual : 14.5G, markov strength of 239
- large organisation : 387.8T, markov strength of 344

In 10 years, 32 times faster (Moore)

- wardriver : 345.6M, markov strength of 202
- individual : 464.5G, markov strength of 273
- large organisation : 12409T, markov strength of 388

Discovery ratio vs. computing power



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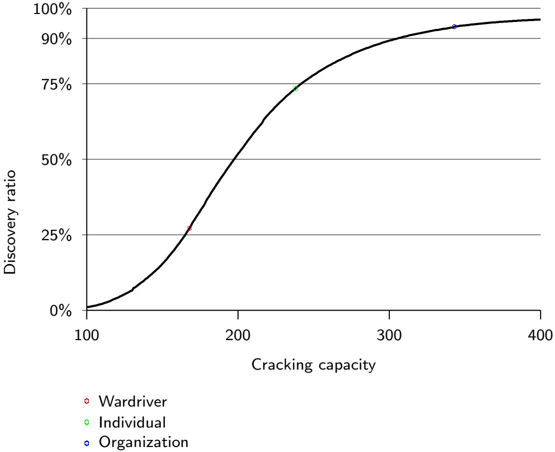

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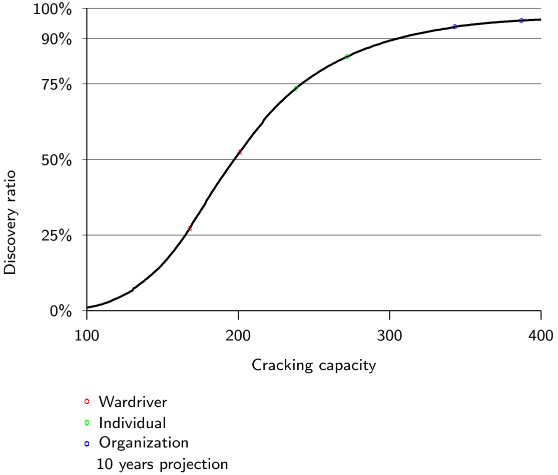

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Usual issues

EAP strength directly linked to good configuration

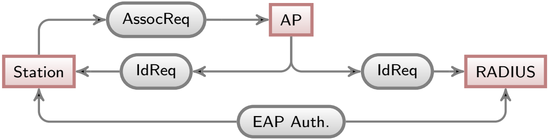
- Good choice in EAP method
- Proper RADIUS authentication

In particular...

Strictly verify RADIUS certificate to avoid MiM

Looking more carefully

AP acts as a relay between client and RADIUS server



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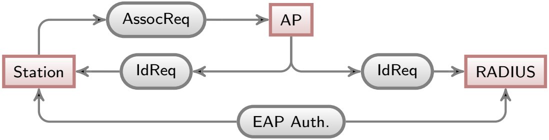

Direct EAP communication between client and RADIUS

What if...

There was an exploitable flaw within EAP ?

- Ability to execute arbitrary code
- Access to RADIUS database
- Access to backend
- Etc.

More importantly

Ability to generate RADIUS traffic !

Of MK transmission

AP notification

When authentication done, RADIUS notifies AP

- EAP Success (3) or Failure (4)
- MK sent using MS-MPPE-Recv-Key (attribute 17)
- HMAC-MD5 message (attribute 80)

Injecting arbitrary MK

- Have your shellcode executed
- Craft a EAP Success
- Put your own MK in MS-MPPE-Recv-Key
- Have it sent to AP

Small issue...

You need to compute HMAC-MD5 message

Bypassing HMAC-MD5

- You don't know RADIUS secret
- But you own the server...

Ideas

- Read secret from conf/memory
- Ask RADIUS to craft packet for you

Product dependant methods

In practice

Some stuff done or to do

- EAP fuzzing (flaws)
- EAP fingerprinting (id)
- Exploits

Then...

Attacker can have his own MK sent back to AP

Not quite the end of it...

Still need to perform 4-Way Handshake

- Hack a WPA/WPA2 supplicant !
- Specific module for wpa_supplicant

Step by step

- Answer EAP Request from AP
- Start EAP dialog to RADIUS
- Trigger the vulnerability
- Deliver exploit
- Grab EAP Success from AP

When you're done...

In the end...

- Rogue client starts authenticating
- Exploits RADIUS server
- Gets authenticated with arbitrary MK
- Finish WPA/WPA2 dialog with AP

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Most importantly...

He can now access the network through Wi-Fi

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PSK selection

Recommandations

- if possible, just use a random 64 bytes value, or one of the safer authentication schemes
- passwords not derived from a known word and with a strength of 400 or more on the Markov scale should be safe for the next years
- just use "chanereaAiO4", it is safe !

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Beware

- the cracker might have a better model for his attacks
- "real" sentences might seem safe because they are long, but are likely to be weak
- crypto flaws might be discovered and exploited

The future of PSK

Automatic key setup

- several proprietary solutions, and a standard
- automagically sets the network and security settings
- removes user input, no more bad keys (hopefully)

Wi-Fi Protected Setup

- standard from the Wi-Fi Alliance
- authenticates the device by
  - in-band : entering a PIN code, pushing a button
  - out-of-band : connecting an USB stick, reading RFIDs
- might be attacked during the first association

EAP considerations

Recommandations

- Carefully choose your EAP method
- Ensure clients can authenticate RADIUS
- Harden your RADIUS box
- Proxy authentication to another AAA server

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Beware

- RADIUS certificate must checked, always
- Against your very own CA, only

The end...

Thank you all for your attention

Questions ?