Brute forcing Wi-Fi Protected Setup

When poor design meets poor implementation.

26.12.2011
Version 3

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Introduction

"Wi-Fi Protected Setup™ is an optional certification program from the Wi-Fi Alliance that is designed to ease the task of setting up and configuring security on wireless local area networks. Introduced by the Wi-Fi Alliance in early 2007, the program provides an industry-wide set of network setup solutions for homes and small office (SOHO) environments.

Wi-Fi Protected Setup enables typical users who possess little understanding of traditional Wi-Fi configuration and security settings to automatically configure new wireless networks, add new devices and enable security. More than 200 products have been Wi-Fi CERTIFIED™ for Wi-Fi Protected Setup since the program was launced (sic!) in January 2007."[1]

The Wi-Fi Simple Configuration Specification (WSC) is the underlying technology for the Wi-Fi Protected Setup certification.

Almost all major vendors (including Cisco/Linksys, Netgear, D-Link, Belkin, Buffalo, ZyXEL and Technicolor) have WPS-certified devices, other vendors (eg. TP-Link) ship devices with WPS-support which are not WPS-certified.

WPS is activated by default on all devices I had access to.

Although WPS is marketed as being a secure way of configuring a wireless device, there are design and implementation flaws which enable an attacker to gain access to an otherwise sufficiently secured wireless network.

Configuration Options Overview

WPS supports out-of-band configuration over Ethernet/UPnP (also NFC is mentioned in the specification) or in-band configuration over IEEE 802.11/EAP. Only in-band configuration will be covered in this paper.

Terminology[2]

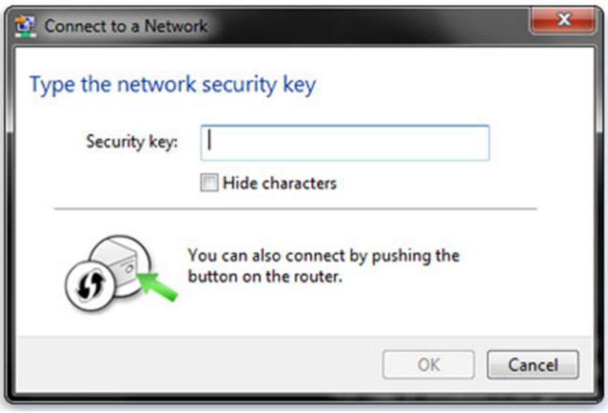
- The **enrollee** is a new device that does not have the settings for the wireless network.
- The **registrar** provides wireless settings to the enrollee.
- The **access point** provides normal wireless network hosting and also proxies messages between the enrollee and the registrar.

[1] http://www.wi-fi.org/wifi-protected-setup/
[2] http://download.microsoft.com/download/a/f/7/af7777e5-7dcd-4800-8a0a-b18336565f5b/WCN-Netspec.doc

Push-Button-Connect (“PBC”)

The user has to push a button, either an actual or virtual one, on both the Access Point and the new wireless client device. PBC on the AP will only be active until authentication has succeeded or timeout after two minutes.

This Option is called **wps_pbc** in wpa_cli[3] (text-based frontend program for interacting with wpa_supplicant).



Connect to a Network

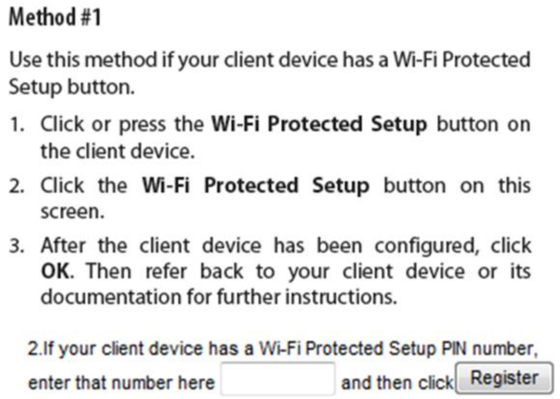
Type the network security key

Security key:

□ Hide characters

You can also connect by pushing the button on the router.

Firgure 1: activated “virtual Push Button” (Windows acts as enrollee) (Windows 7)



Method #1

Use this method if your client device has a Wi-Fi Protected Setup button.

1. Click or press the **Wi-Fi Protected Setup** button on the client device.
2. Click the **Wi-Fi Protected Setup** button on this screen.
3. After the client device has been configured, click **OK**. Then refer back to your client device or its documentation for further instructions.

2.If your client device has a Wi-Fi Protected Setup PIN number, enter that number here and then click Register

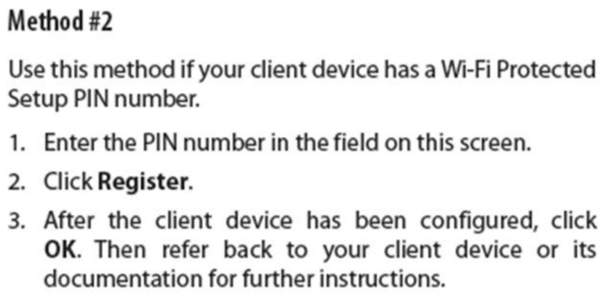
Figure 2: Description of PBC option (Linksys WRT320N User Manual)

PIN

Internal Registrar

The user has to enter the PIN of the Wi-Fi adapter into the web interface of the access point. The PIN can either be printed on the label of the adapter or generated by software.

This option is called **wps_pin** in wpa_cli.

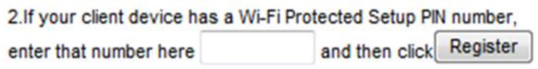


Method #2

Use this method if your client device has a Wi-Fi Protected Setup PIN number.

1. Enter the PIN number in the field on this screen.
2. Click **Register**.
3. After the client device has been configured, click **OK**. Then refer back to your client device or its documentation for further instructions.

Figure 3: Description of PIN internal Registrar option (Linksys WRT320N User Manual)



2.If your client device has a Wi-Fi Protected Setup PIN number, enter that number here and then click Register

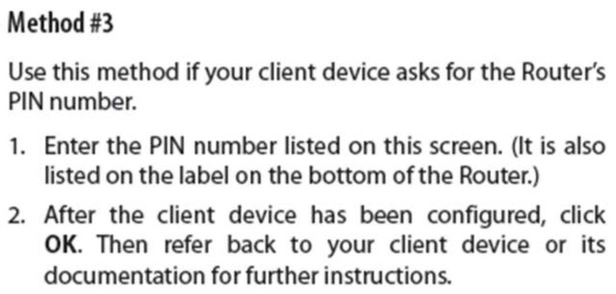
Figure 4: PIN field – Router is Registrar (Linksys WRT320N Web Interface)

[3] http://hostap.epitest.fi/wpa_supplicant/

External Registrar

The user has to enter the PIN of the access point into a form on the client device (eg. computer).

This option is called **wps_reg** in wpa_cli.

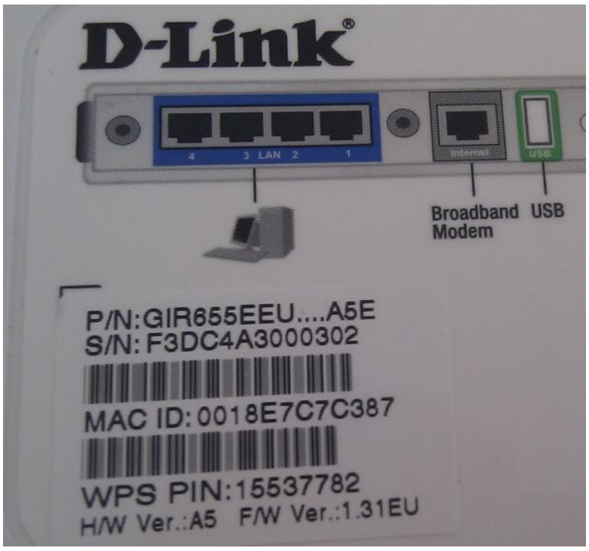


Method #3

Use this method if your client device asks for the Router's PIN number.

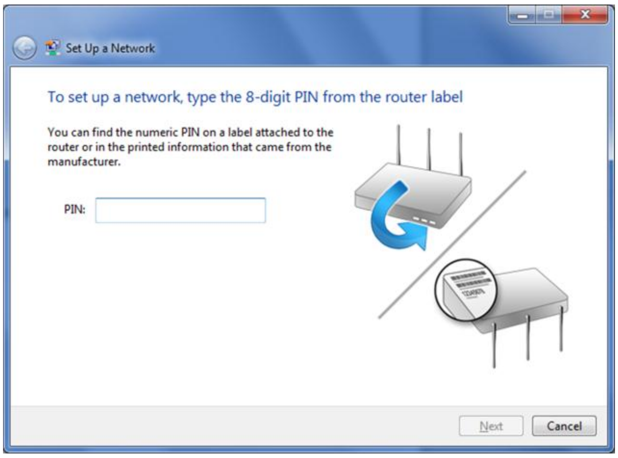
1. Enter the PIN number listed on this screen. (It is also listed on the label on the bottom of the Router.)
2. After the client device has been configured, click **OK**. Then refer back to your client device or its documentation for further instructions.

Figure 5: Description of PIN external Registrar option (Linksys WRT320N User Manual)



P/N:GIR655EEU....A5E
S/N: F3DC4A3000302
MAC ID: 0018E7C7C387
WPS PIN:15537782
H/W Ver.:A5 F/W Ver.:1.31EU

Figure 7: Label with WPS PIN on the back of a D-Link router



To set up a network, type the 8-digit PIN from the router label

You can find the numeric PIN on a label attached to the router or in the printed information that came from the manufacturer.

PIN:

Figure 6: Windows Connect Now Wizard acting as a Registrar (Windows 7)

Design Flaw #1

Option / Authentication	Physical Access	Web Interface	PIN
Push-button-connect	X		
PIN – Internal Registrar		X	
PIN – External Registrar			X

WPS Options and which kind of authentication they actually use.

As the External Registrar option does not require any kind of authentication apart from providing the PIN, it is potentially vulnerable to brute force attacks.

Authentication (PIN – External Registrar)[4]

IEEE 802.11			
	Supplicant → AP	Authentication Request	802.11 Authentication
	Supplicant ← AP	Authentication Response	
	Supplicant → AP	Association Request	802.11 Association
	Supplicant ← AP	Association Response	
IEEE 802.11/EAP			
	Supplicant → AP	EAPOL-Start	EAP Initiation
	Supplicant ← AP	EAP-Request Identity	
	Supplicant → AP	EAP-Response Identity (Identity: “WFA-SimpleConfig-Registrar-1-0”)	
IEEE 802.11/EAP Expanded Type, Vendor ID: WFA (0x372A), Vendor Type: SimpleConfig (0x01)			
M1	Enrollee → Registrar	N1 || Description || PK_E	Diffie-Hellman Key Exchange
M2	Enrollee ← Registrar	N1 || N2 || Description || PK_R || Authenticator	
M3	Enrollee → Registrar	N2 || E-Hash1 || E-Hash2 || Authenticator	
M4	Enrollee ← Registrar	N1 || R-Hash1 || R-Hash2 || $E_{KeyWrapKey}$(R-S1) || Authenticator	proove posession of 1st half of PIN
M5	Enrollee → Registrar	N2 || $E_{KeyWrapKey}$(E-S1) || Authenticator	proove posession of 1st half of PIN
M6	Enrollee ← Registrar	N1 || $E_{KeyWrapKey}$(R-S2) || Authenticator	proove posession of 2nd half of PIN
M7	Enrollee → Registrar	N2 || $E_{KeyWrapKey}$(E-S2 ||ConfigData) || Authenticator	proove posession of 2nd half of PIN, send AP configuration
M8	Enrollee ← Registrar	N1 || $E_{KeyWrapKey}$(ConfigData) || Authenticator	set AP configuration

Enrollee = AP
Registrar = Supplicant = Client/Attacker
 	
PK_E = Diffie-Hellman Public Key Enrollee
PK_R = Diffie-Hellman Public Key Registrar
Authkey and KeyWrapKey are derived from the Diffie-Hellman shared key.
 	
Authenticator = $HMAC_{Authkey}$(last message || current message)
 	
$E_{KeyWrapKey}$ = Stuff encrypted with KeyWrapKey (AES-CBC)
	PSK1 = first 128 bits of $HMAC_{AuthKey}$(1st half of PIN)
	PSK2 = first 128 bits of $HMAC_{AuthKey}$(2nd half of PIN)
	
	E-S1 = 128 random bits
	E-S2 = 128 random bits
	E-Hash1 = $HMAC_{AuthKey}$(E-S1 || PSK1 || PK_E || PK_R)
	E-Hash2 = $HMAC_{AuthKey}$(E-S2 || PSK2 || PK_E || PK_R)
	
	R-S1 = 128 random bits
	R-S2 = 128 random bits
	R-Hash1 = $HMAC_{AuthKey}$(R-S1 || PSK1 || PK_E || PK_R)
	R-Hash2 = $HMAC_{AuthKey}$(R-S2 || PSK2 || PK_E || PK_R)

1	2	3	4	5	6	7	0
1st half of PIN				2nd half of PIN			checksum

If the WPS-authentication fails at some point, the AP will send an EAP-NACK message.

[4] based on http://download.microsoft.com/download/a/f/7/af7777e5-7dcd-4800-8a0a-b18336565f5b/WCN-Netspec.doc

Design flaw #2

An attacker can derive information about the correctness of parts the PIN from the AP´s responses.

- If the attacker receives an EAP-NACK message after sending M4, he knows that the 1st half of the PIN was incorrect.
- If the attacker receives an EAP-NACK message after sending M6, he knows that the 2nd half of the PIN was incorrect.

This form of authentication dramatically decreases the maximum possible authentication attempts needed from 10^8 (=100.000.000) to $10^4 + 10^4$ (=20.000).

As the 8th digit of the PIN is always a checksum of digit one to digit seven, there are at most $10^4 + 10^3$ (=11.000) attempts needed to find the correct PIN.

Brute Force Methodology

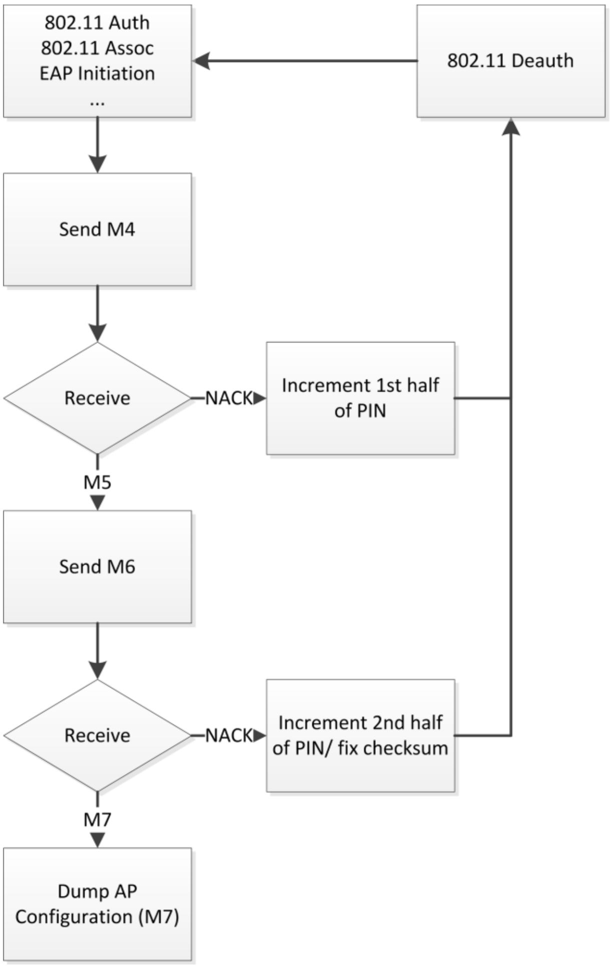


Figure 8: Flowchart showing how an optimized brute force attack works

Brute Force Implementation

A proof-of-concept brute force tool was implemented in Python. It uses the Scapy[5] Library for decoding, generating, sending and receiving packets. This tool was used on several routers made by different vendors.

Sample output

```
sniffer started

trying 00000000
attempt took 0.95 seconds
trying 00010009
attempt took 1.28 seconds
trying 00020008
attempt took 1.03 seconds

<snip>

trying 18660005
attempt took 1.08 seconds
trying 18670004              # found 1st half of PIN
attempt took 1.09 seconds
trying 18670011
attempt took 1.08 seconds
trying 18670028
attempt took 1.17 seconds
trying 18670035
attempt took 1.12 seconds

<snip>

trying 18674071
attempt took 1.15 seconds
trying 18674088
attempt took 1.11 seconds

trying 18674095              # found 2nd half of PIN
E-S2:
0000   16 F6 82 CA A8 24 7E 98  85 4C BD A6 BE D9 14 50   .....$~..L.....P
SSID:
0000   74 70 2D 74 65 73 74                               tp-test
MAC:
0000   F4 EC 38 CF AC 2C                                  ..8..,
Auth Type:
0000   00 20                                              .
Encryption Type:
0000   00 08                                              ..
Network Key:
0000   72 65 61 6C 6C 79 5F 72  65 61 6C 6C 79 5F 6C 6F   really_really_lo
0010   6E 67 5F 77 70 61 5F 70  61 73 73 70 68 72 61 73   ng_wpa_passphras
0020   65 5F 67 6F 6F 64 5F 6C  75 63 6B 5F 63 72 61 63   e_good_luck_crac
0030   6B 69 6E 67 5F 74 68 69  73 5F 6F 6E 65            king_this_one
Key Wrap Algorithm:
0000   76 3C 7A 87 0A 7D F7 E5                            v<z..}..
```

[5] http://www.secdev.org/projects/scapy/

Results

Authentication attempt duration

One authentication attempt usually took between 0.5 and 3 seconds to complete. It was observed that the calculation of the Diffie-Hellman Shared Key (needs to be done before generating M3) on the AP took a big part of the authentication time. This can be speeded up by choosing a very small DH Secret Number, thus generating a very small DH Public Key and making Shared Key calculation on the AP's side easier.

Implementation Flaws

Some vendors did not implement any kind of blocking mechanism to prevent brute force attacks. This allows an attacker to try all possible PIN combinations in less than four hours (at 1.3 seconds/attempt).

On average an attack will succeed in half the time.

The Netgear device has lock down functionality implemented, but the lock down phases are not long enough to make an attack impractical. In this case an attack will on average succeed in less than a day (timing data can be found on the next page).

Vendor	Device Name	HW-Version	FW-Version	Lock down	WPS-certified
D-Link	DIR-655	A4 (Web Interface) A5 (Label)	1.35	No	Yes
Linksys	WRT320	1.0	1.0.04	?[6]	Yes
Netgear	WGR614v10	?	1.0.2.26	Yes	Yes
TP-Link	TL-WR1043ND	1.8	V1_110429	No	No

Firmware versions are up-to-date as of 18.10.2011.

In rare cases devices started to send malformed messages or their web interface and routing did not work properly anymore. A reboot was needed to solve the problem. This might be evidence of some kind of corruption, but was not investigated further.

[6] WPS-functionality always stopped to work somewhere between 2 and 150 failed authentication attempts. The functionality did not even return after several hours. I would consider this a bug in the firmware which causes a DoS rather than lock-down functionality.

Mitigations

End users

Deactivate WPS. This may not always be possible.

Vendors

Introduce sufficiently long lock-down periods in order to make an attack impractical. Of course this requires a new firmware release.

Attempts before lock	Lock down time	Attempts per minute	Maximum attack time	Maximum attack time	Comment
11000	0 minutes	46.15	3.97 hours	0.17 days	no lock down
?[7]		4.20	43,65 hours	1,82 days	Netgear WGR614v10
3	1 minutes	2.82	65.08 hours	2.71 days	Requirement for WSC 2.0
15	60 minutes	0.25	737.31 hours	30.72 days	Lock down configurations making brute force less practical
10	60 minutes	0.17	1103.97	46.00 days	
5	60 minutes	0.08	2203.97	91.83 days	

Assumed time per attempt: 1.3 seconds

Considering that an AP typically runs for several months, a determined attacker might still be able to successfully attack a WPS-enabled AP. This attack is low-cost and has a high success guarantee compared to cracking WPA/WPA2-PSK.

Conclusion

As nearly all major router/AP vendors have WPS-certified devices and WPS – PIN (External Registrar) is mandatory for certification, it is expected that a lot of devices are vulnerable to this kind of attack.

Having a sufficiently long lock-down period is most likely not a requirement for certification. However it might be a requirement in the (new) WSC Specification Version 2[8]. I contacted the Wi-Fi Alliance about this – they have yet to respond.

Collaboration with vendors will be necessary for identifying all vulnerable devices. It is up to the vendors to implement mitigations and release new firmware.

Affected end-users will have to be informed about this vulnerability and advised to disable WPS or update their firmware to a more secure version (if available).

[7] No consistent lock down pattern was found. However on average about 4.20 authentication attempts per minute were possible.

[8] http://www.wi-fi.org/files/20110421_China_Symposia_full_merge.pdf