Attacking GlobalPlatform SCP02-compliant Smart Cards Using a Padding Oracle Attack

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1. Description of SCP02
2. Padding oracle attack
3. Experimental results
4. Conclusion

Context

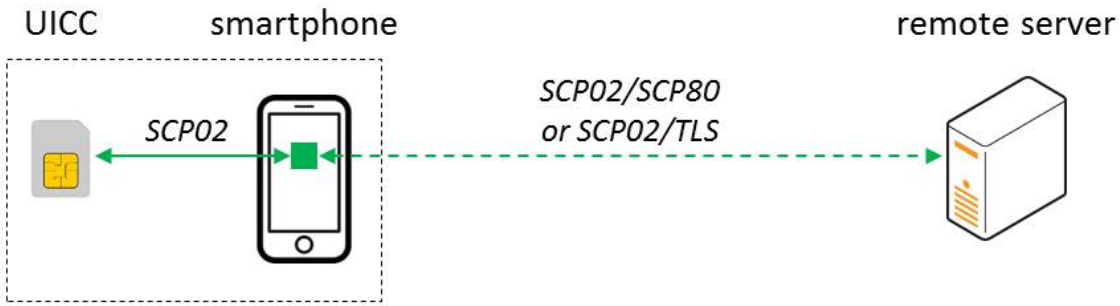
- Security protocol promoted by GlobalPlatform (association that aims at promoting standard, interoperable mechanisms related to the chip technology)
- Element of a set of security protocols: SCP03, SCP80, SCP81, etc.
- Likely the most widely used SCP protocol

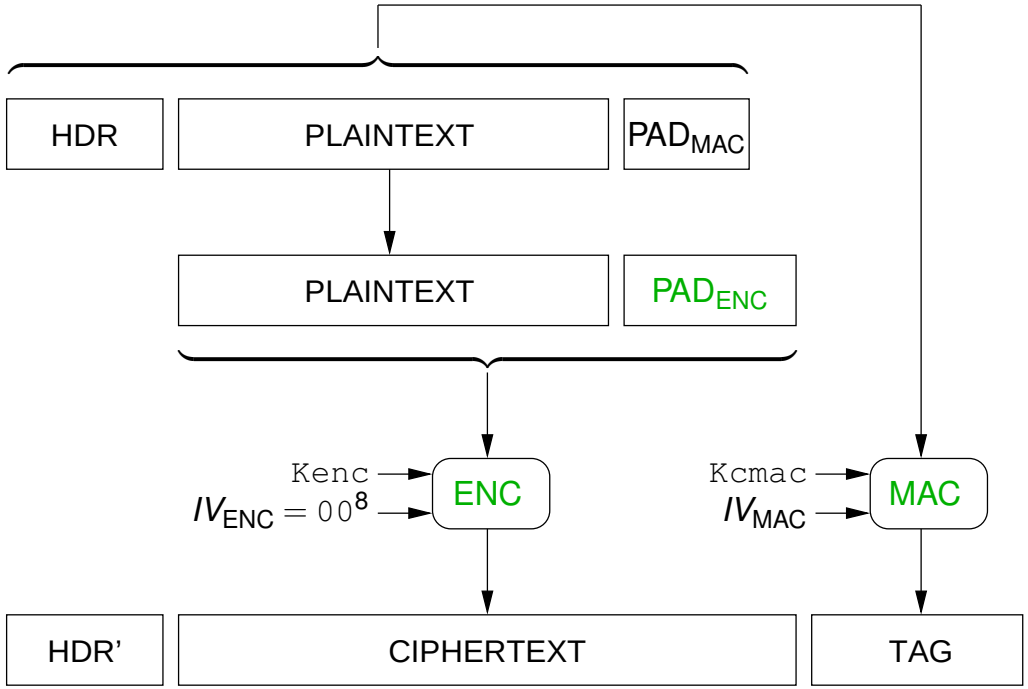
Cryptographic functions

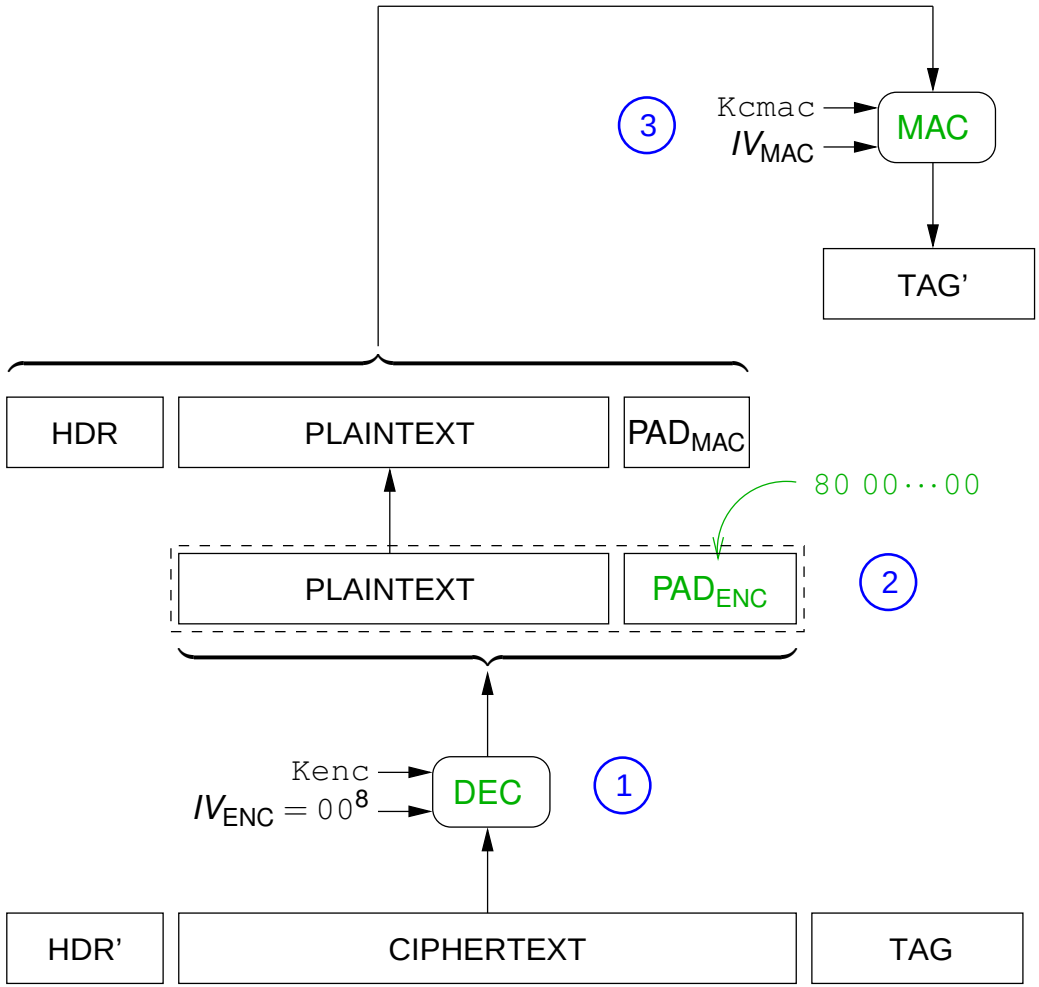
- Based on DES/3DES (encryption and MAC; cf. [ISO9797-1] and [ISO10116])

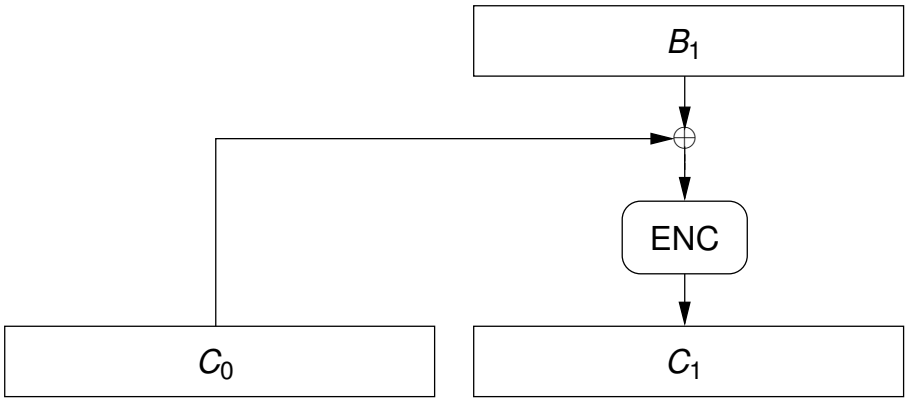
Purpose

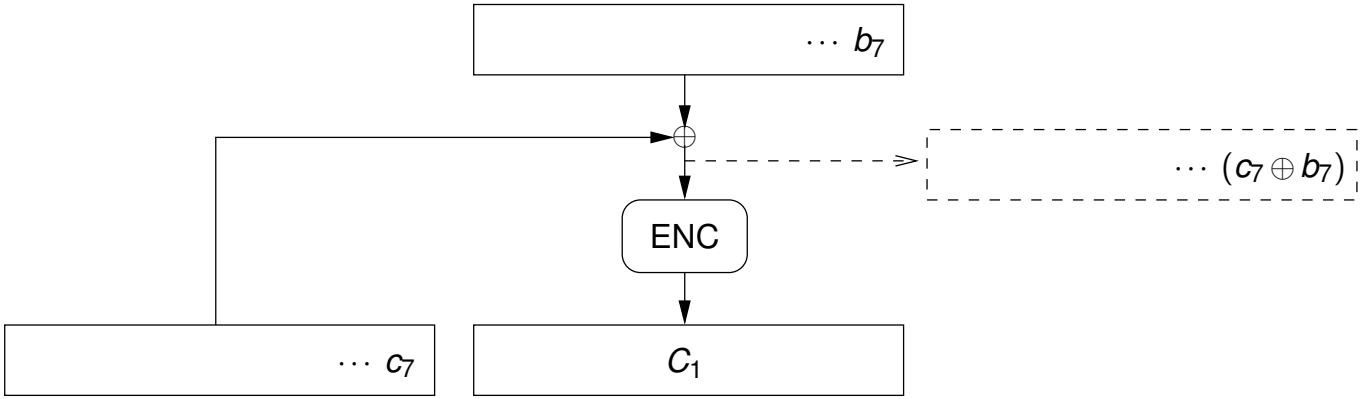
- Secure channel between an "*off card entity*" and a card
- Different security levels: integrity, confidentiality, both
- Remote card management (e.g., applet upload into an UICC/SIM card)

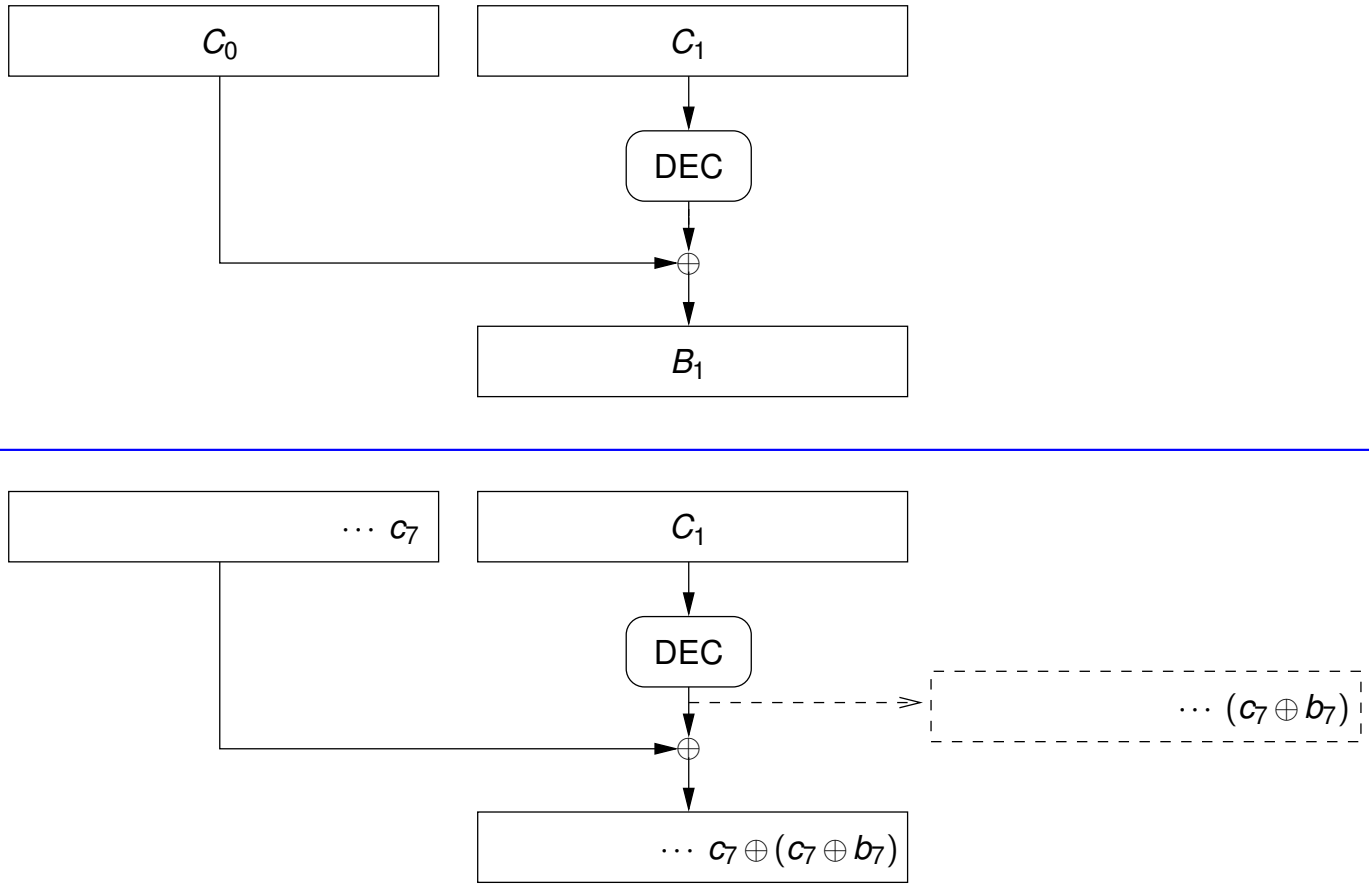


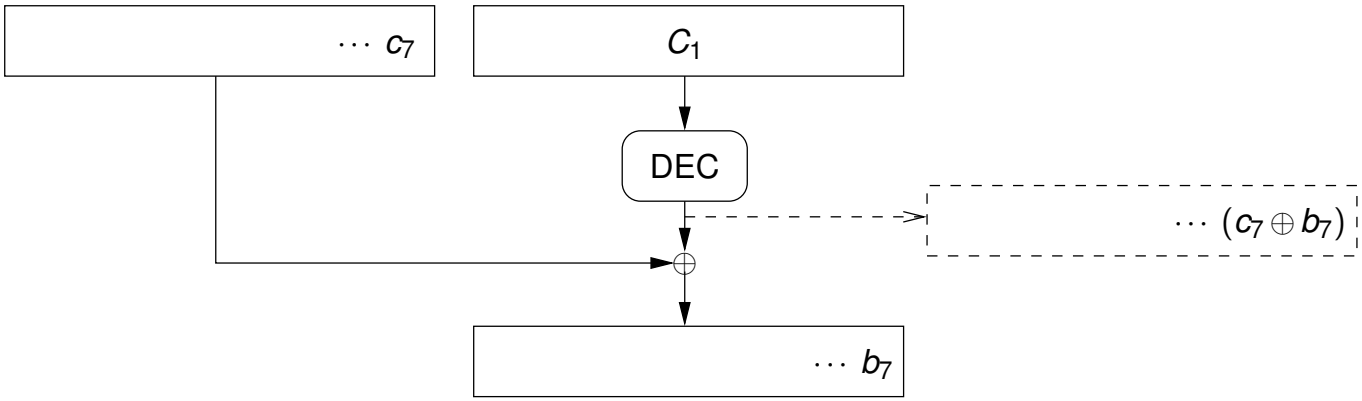

HDR
PLAINTEXT
PAD_MAC
PLAINTEXT
PAD_ENC
Kenc
IV_ENC = 00^8
ENC
Kcmac
IV_MAC
MAC
HDR'
CIPHERTEXT
TAG

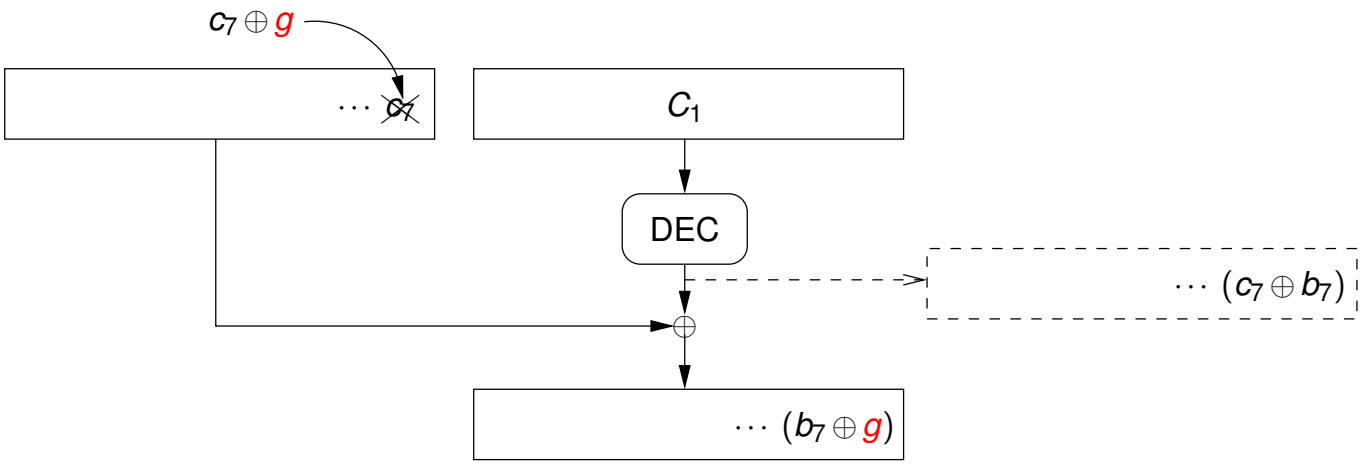

3
Kcmac
IV_{MAC}
MAC
TAG'
HDR
PLAINTEXT
PAD_{MAC}
80 00···00
PLAINTEXT
PAD_{ENC}
2
Kenc
$IV_{ENC} = 00^8$
DEC
1
HDR'
CIPHERTEXT
TAG

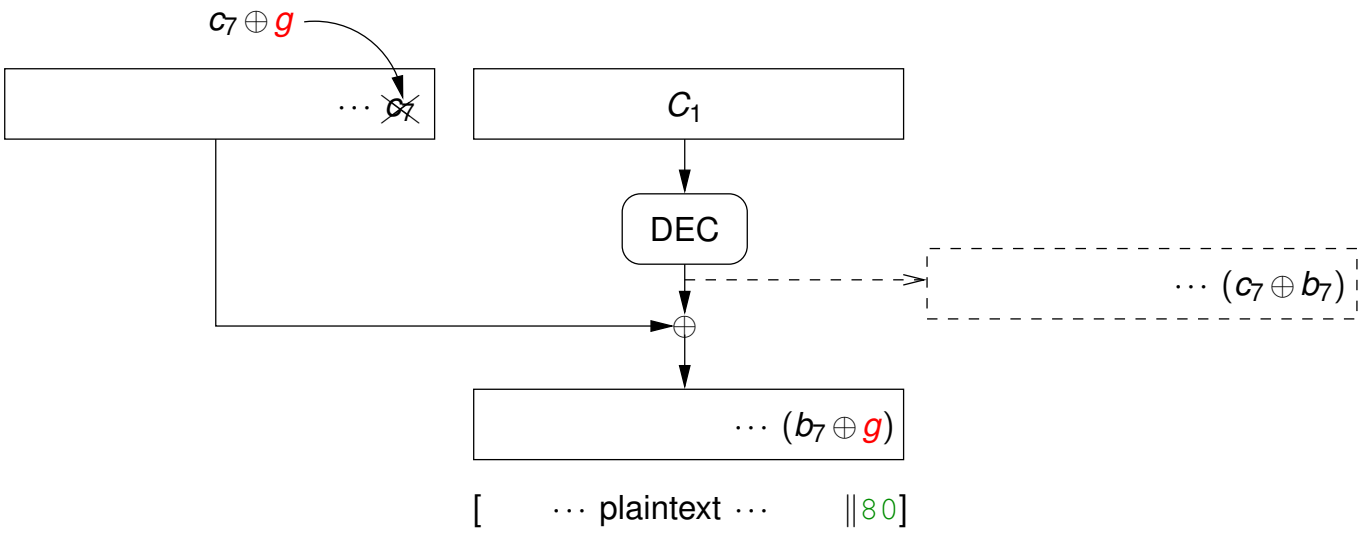

B_1
ENC
C_0
C_1

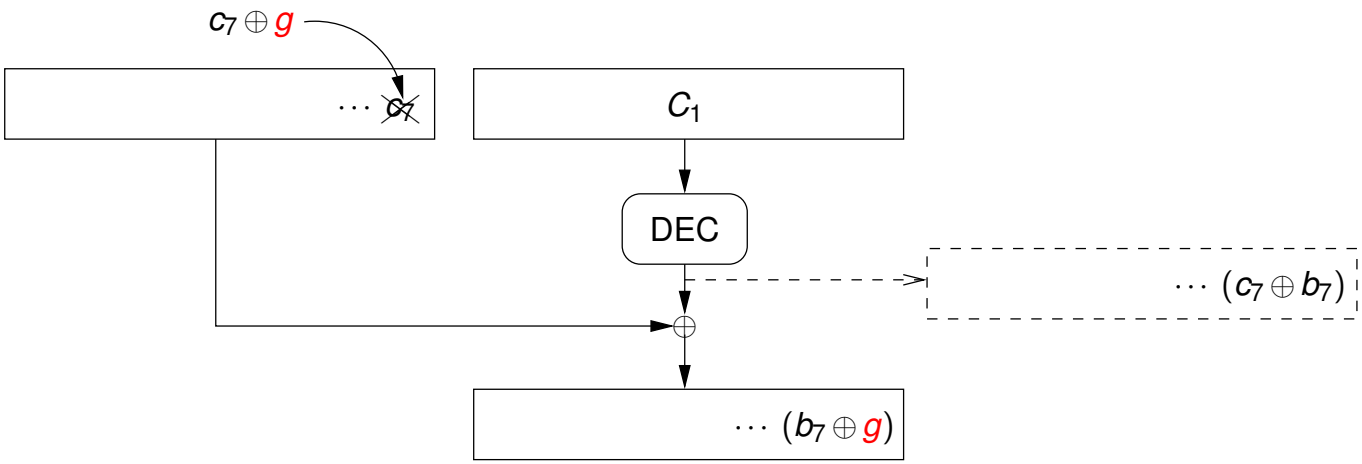

$\cdots b_7$
$\cdots (c_7 \oplus b_7)$
ENC
$\cdots c_7$
C_1


C_0
C_1
DEC
B_1
$\cdots c_7$
C_1
DEC
$\cdots (c_7 \oplus b_7)$
$\cdots c_7 \oplus (c_7 \oplus b_7)$

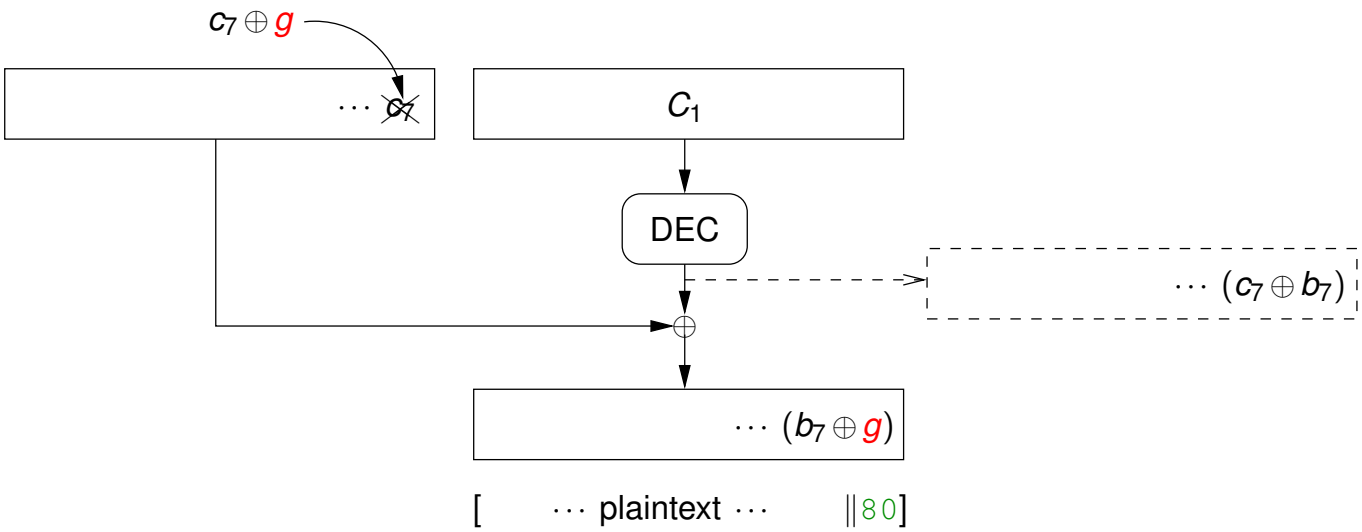

$\cdots c_7$
C_1
DEC
$\cdots (c_7 \oplus b_7)$
$\cdots b_7$


$c_7 \oplus g$
$\cdots$ c_7
C_1
DEC
$\cdots$ $(c_7 \oplus b_7)$
$\cdots$ $(b_7 \oplus g)$

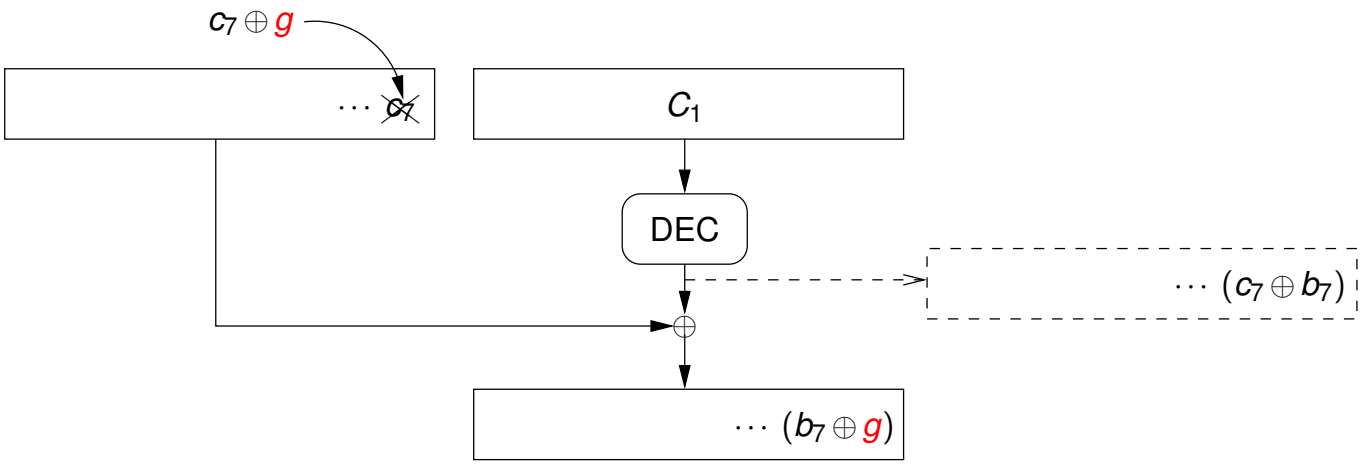

$c_7 \oplus g$
$\cdots$ c_7
C_1
DEC
$\cdots$ $(c_7 \oplus b_7)$
$\cdots$ $(b_7 \oplus g)$
[$\cdots$ plaintext $\cdots$ ‖80]



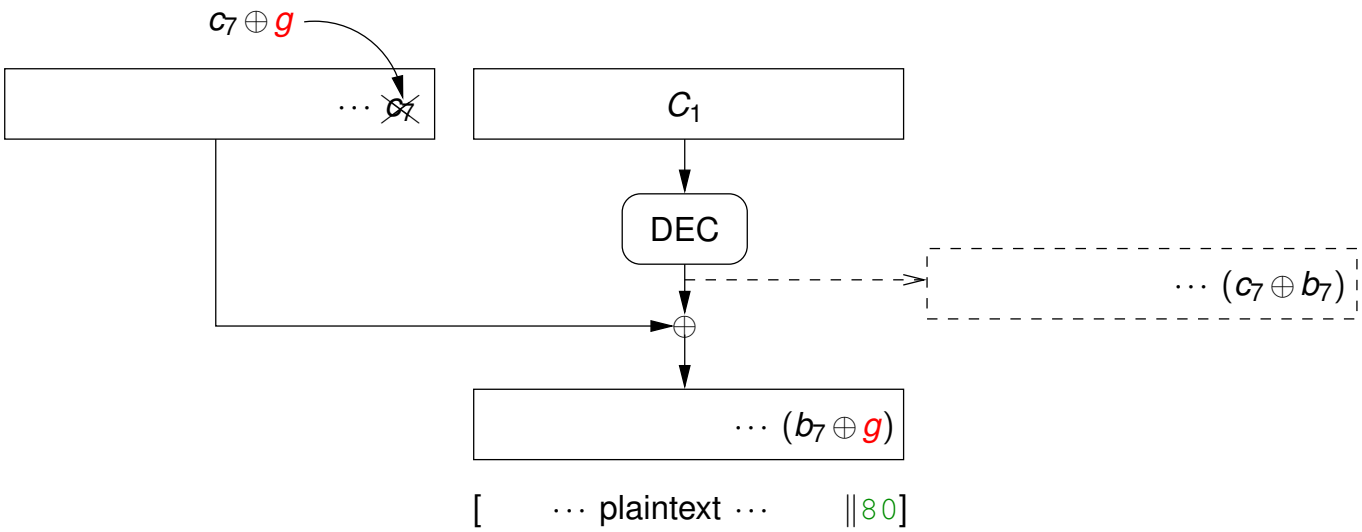
$g = 13$ $\Rightarrow$ $\Rightarrow$ invalid padding



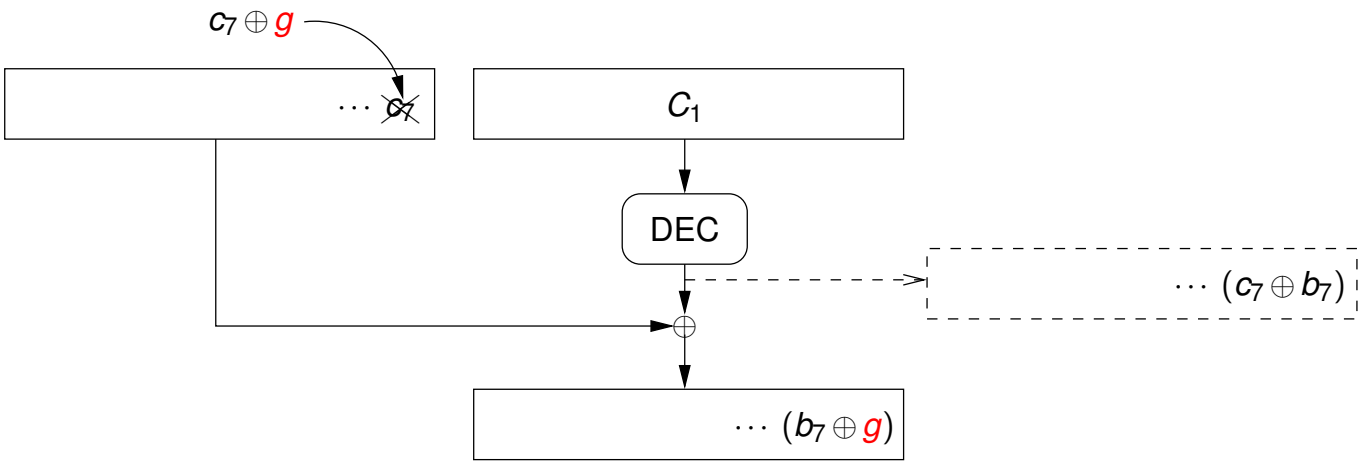
$g = 13$ $\Rightarrow$ $\Rightarrow$ invalid padding
$g = 14$ $\Rightarrow$ $\Rightarrow$ invalid padding



$g = 13$	$\Rightarrow$		$\Rightarrow$	invalid padding
$g = 14$	$\Rightarrow$		$\Rightarrow$	invalid padding
$g = 15$	$\Rightarrow$		$\Rightarrow$	invalid padding



$g = 13$	$\Rightarrow$		$\Rightarrow$	invalid padding
$g = 14$	$\Rightarrow$		$\Rightarrow$	invalid padding
$g = 15$	$\Rightarrow$		$\Rightarrow$	invalid padding
$g = 16$	$\Rightarrow$		$\Rightarrow$	invalid padding



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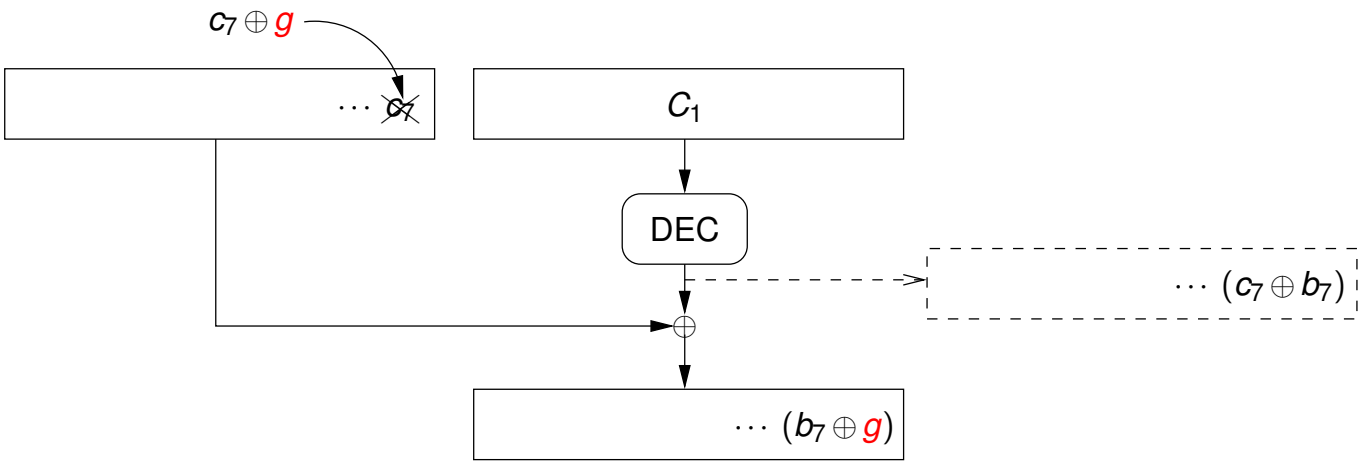
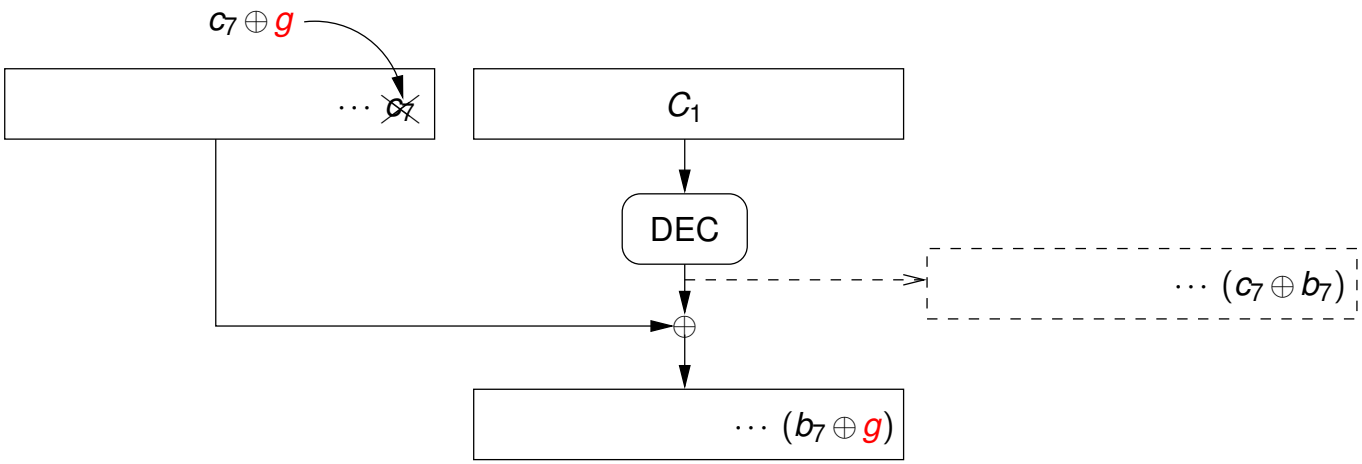
$g = 16$	$\Rightarrow$		$\Rightarrow$	invalid padding
$g = 17$	$\Rightarrow$		$\Rightarrow$	valid padding



$g = 13$	$\Rightarrow$	$b_7 \oplus g = 76$	$\Rightarrow$	invalid padding		
$g = 14$	$\Rightarrow$	$b_7 \oplus g = 77$	$\Rightarrow$	invalid padding		
$g = 15$	$\Rightarrow$	$b_7 \oplus g = 78$	$\Rightarrow$	invalid padding		
$g = 16$	$\Rightarrow$	$b_7 \oplus g = 79$	$\Rightarrow$	invalid padding		
$g = 17$	$\Rightarrow$	$b_7 \oplus g = 80$	$\Rightarrow$	valid padding	$\Rightarrow$	$b_7 = g \oplus 80 = 97$



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$g = 17$	$\Rightarrow$	$b_7 \oplus g = 80$	$\Rightarrow$	valid padding	$\Rightarrow$	$b_7 = g \oplus 80 = 97$

- The validity of padding data indicates whether b_7 can be found or not.
- Technique called “padding oracle attack” due to Vaudenay in 2002 [V02].

- How to know if the padding data is valid or invalid (after decryption)?

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Error message (e.g., WTLS [V02])	ERR_DEC	ERR_MAC
Computation time (e.g., TLS 1.0 [CHVV03])	time ↘	time ↗

- The smart card sends *always* a response (status word).
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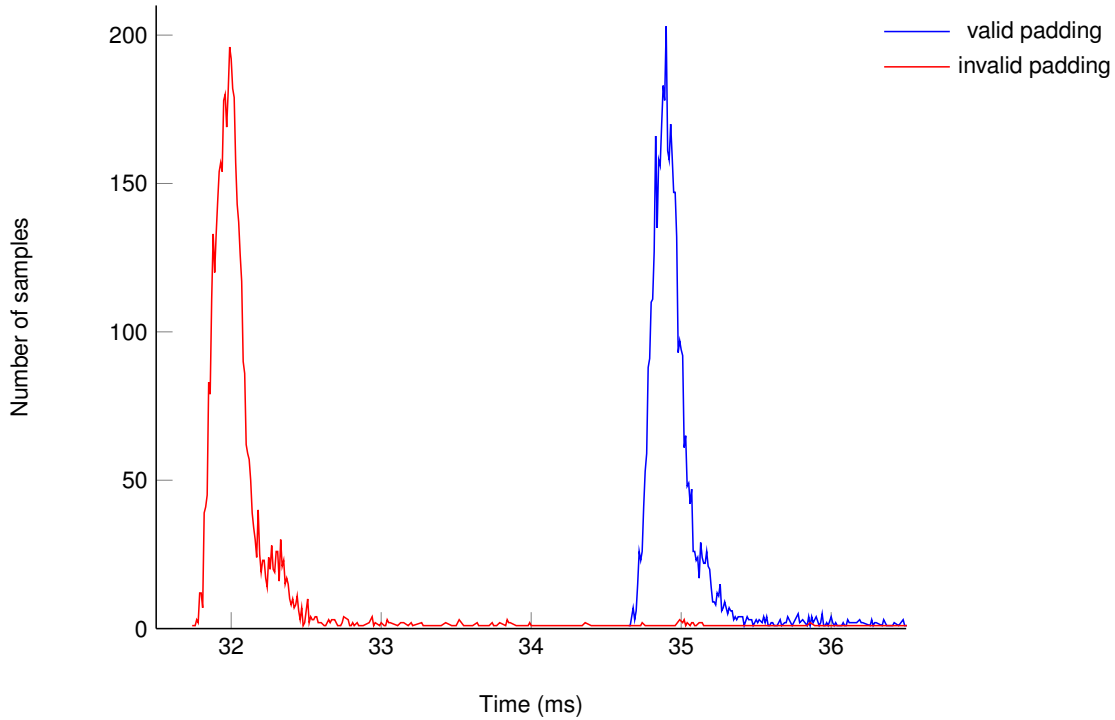
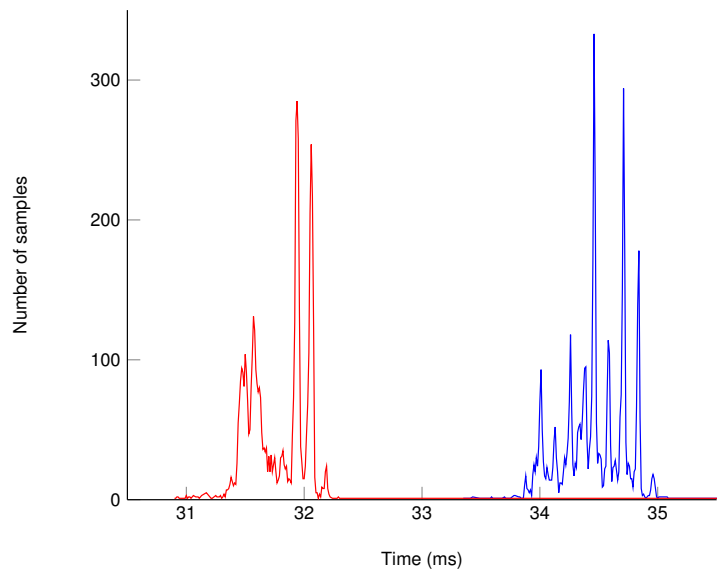
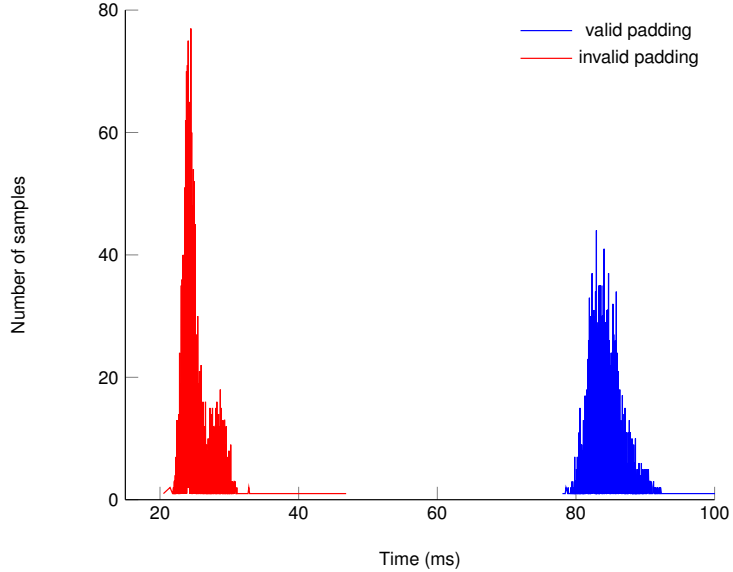
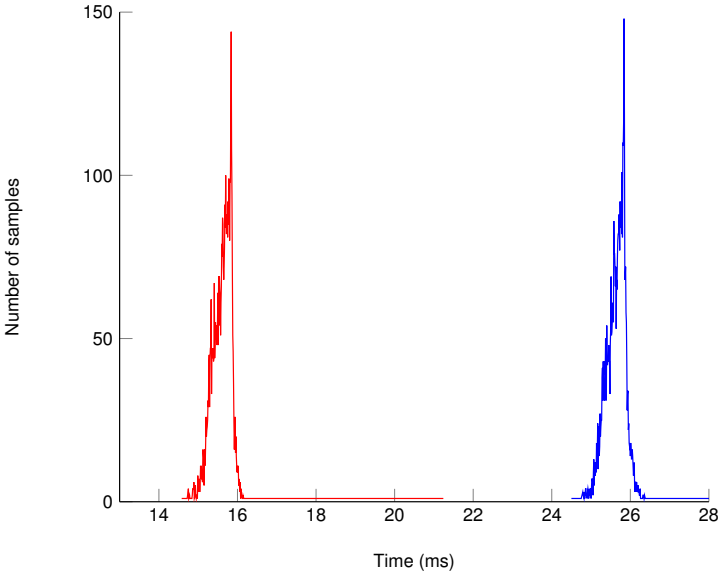
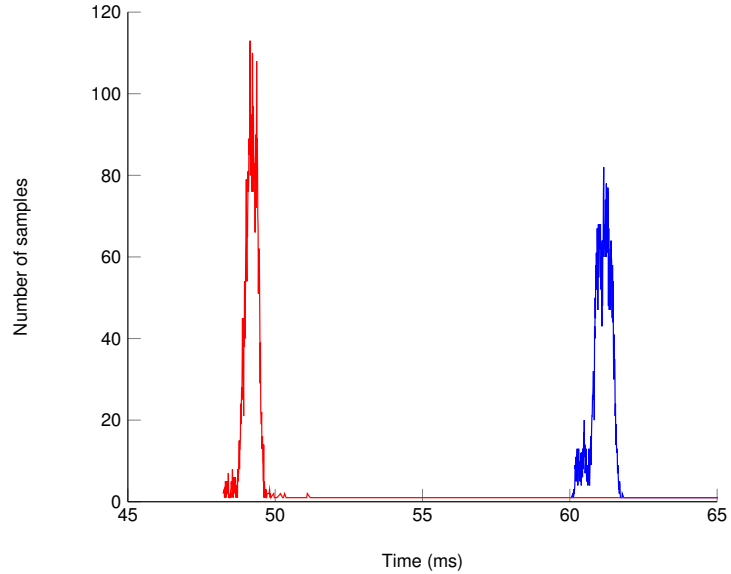


- The card response time reflects the card computation time ⇒ suitable padding oracle


Number of samples
300
200
100
0
31
32
33
34
35
Time (ms)


valid padding
invalid padding
Number of samples
80
60
40
20
0
20
40
60
80
100
Time (ms)


Number of samples
150
100
50
0
14
16
18
20
22
24
26
28
Time (ms)


Number of samples
120
100
80
60
40
20
0
45
50
55
60
65
Time (ms)

- Experimental setting: card connected to a card reader (4 card readers, wired and wireless)
- 10 smart cards from 6 card manufacturers
- SIM cards, generic Java cards

- Experiment: find a 16-byte secret key sent to the smart card in an encrypted SCP02 command
- 300 experiments/card $\Rightarrow$ 100 % success
- Practical complexity $\in [127.75, 133.38]$ close to best average case (128)
- Time to find 16 bytes: 2.7 mn to 11.4 mn (variable response time from the smart card)

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$\Rightarrow$ Padding oracle attack is applicable against SCP02.

$\Rightarrow$ Among all the deployed smart cards (including 6 billion SIM cards), how many may be impacted?

- Possible real-life scenario: upload of an applet embedding a secret key (e.g., transportation, banking) into the UICC/SIM card.

1. The victim downloads from a popular store an infected application into his smartphone. The application embeds a Trojan ✹ (e.g., Tordow [K16], Dvmap [U17]).
2. The Trojan gets access to the memory space of the legitimate application ■ (through privileges escalation).
3. The Trojan can apply the attack: it reads, and modifies the encrypted SCP02 commands received by the legitimate application.
4. The Trojan repeatedly triggers the installation/deinstallation of the applet $\Rightarrow$ the secret key is repeatedly sent through (new) SCP02 channels.

- Correct implementation (not possible for deployed cards)
- Use additional security mechanisms (if such mechanisms are available)
- Use `PUT KEY` command to send sensitive data (dictionary attack applicable [ST16])
- Do not send too many times the same data (server side)

- The padding oracle attack against SCP02-compliant smart cards is possible because of
  - a theoretical flaw lying in the SCP02 protocol (Encrypt-and-MAC scheme),
  - exploited by means of a timing side-channel provided by the smart cards (implementation).
- Several requirements to be fulfilled in order for the attack to be successful.
- Practical attack
  - Experimental setting: 10 smart cards from 6 manufacturers.
  - How many smart cards impacted in real life?
- Responsible disclosure (October 2017-April 2018): card manufacturers, GlobalPlatform.
- SCP02 is now deprecated (March 2018): use SCP03 instead.

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[SCP02] GlobalPlatform. *GlobalPlatform – Card Specification*, version 2.3.1, ref. GPC_SPE_034, March 2018.

[SCP03] GlobalPlatform. *GlobalPlatform Card Technology – Secure Channel Protocol '03' – Card Specification v2.2 – Amendment D*, version 1.1, ref. GPC_SPE_014, July 2014.

[ISO9797-1] ISO/IEC JTC 1/SC 27. *ISO/IEC 9797-1:2011 – Information technology – Security techniques – Message Authentication Codes (MACs) – Part 1: Mechanisms using a block cipher*, 2011.

[ISO10116] ISO/IEC JTC 1/SC 27. *ISO/IEC 10116:2017 – Information technology – Security techniques – Modes of operation for an n-bit block cipher*, 2017.

[ISO7816-4] ISO/IEC JTC 1/SC 17. *ISO/IEC 7816-4:2013 – Information technology – Identification cards – Integrated circuit cards – Part 4: Organization, security and commands for interchange*, 2013.

[V02] S. Vaudenay. *Security Flaws Induced by CBC Padding – Applications to SSL, IPSEC, WTLS...* In L. R. Knudsen, editor, *Advances in Cryptology – EUROCRYPT 2002*. LNCS, vol. 2332, pp. 534-545. Springer, 2002.

[CHVV03] B. Canvel, A. Hiltgen, S. Vaudenay, M. Vuagnoux. *Password interception in a SSL/TLS channel*. In D. Boneh, editor, *Advances in Cryptology – CRYPTO 2003*. LNCS, vol. 2729, pp. 583-599. Springer, 2003.

[ST16] M. Sabt, J. Traoré. *Cryptanalysis of GlobalPlatform Secure Channel Protocols*. In L. Chen, D. McGrew, C. Mitchell, editors, *Security Standardisation Research – SSR 2016*. LNCS, vol. 10074, pp. 62-91. Springer, 2016.

[K16] A. Kivva. *The banker that can steal anything*, 20/09/2016. Available via `https://securelist.com/the-banker-that-can-steal-anything/76101/`.

[U17] R. Unuchek. *Dvmap: the first Android malware with code injection*, 08/06/2017. Available via `https://securelist.com/dvmap-the-first-android-malware-with-code-injection/78648/`.

M	C	μ_W (ms)	μ_R (ms)	t_{min} (ms)	m	τ_+ (%)	K_W	K_R	Z	Z/n
1	A	39.60	42.59	41.00	28	0.16	1	3	2055.71	128.48
	B	40.19	43.94	42.00	28	0.44	1	3	2077.78	129.86
2	C	25.17	84.34	75.00	0	0.00	1	2	2043.95	127.75
	D	26.64	34.36	32.00	0	0.00	1	2	2066.54	129.16
3	E	15.61	25.65	23.00	0	0.00	1	2	2134.03	133.38
4	F	31.81	34.48	33.00	28	0.48	1	3	2109.71	131.86
	G	15.64	18.53	17.00	0	0.28	1	3	2103.62	131.48
5	H	25.18	84.86	72.00	0	0.00	1	2	2048.34	128.02
6	I	25.90	35.85	32.00	0	0.06	1	3	2108.60	131.79
	J	14.32	19.92	17.50	0	0.10	1	2	2094.85	130.93

1. The attacker sits between the remote server and the card at a point where she can directly eavesdrop on SCP02 encrypted commands and send modified commands to the card.
2. The attacker is able to discriminate response times corresponding to a valid and an invalid padding.
3. The remote server repeatedly sets up a (new) secure channel with the card.
4. The same secret information is sent through each such secure channel.
5. The secret information is sent at a predictable position.

NB: req. 4 $\Rightarrow$ req. 3 (and 5)