NTNU | Norwegian University of Science and Technology

SIDE-CHANNEL ATTACKS 3

TTM4205 – Lecture 9

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Contents

Contents

Reference Group Meeting

We had a reference group meeting on Thursday last week and the minutes are available online. A short summary:

- Lectures:
  - Will include more concrete examples
  - Will include book chapter references
- Exercises:
  - Will add hints to some of the problems
  - Will explain what a "break" means
  - Incomplete solutions can give points
- We will not record any lectures

Contents

SCA on PKC

- Timing or power traces can leak secret bits
- Fault injection might leak dummy operations
- Differential analysis allow statistical attacks
- The adversary can choose the input (adaptively)
- The secret key might be static and re-used

Protecting PKC

- Constant time operations and algorithms
- The result must depend on all operations
- Randomize input and/or secrets each n

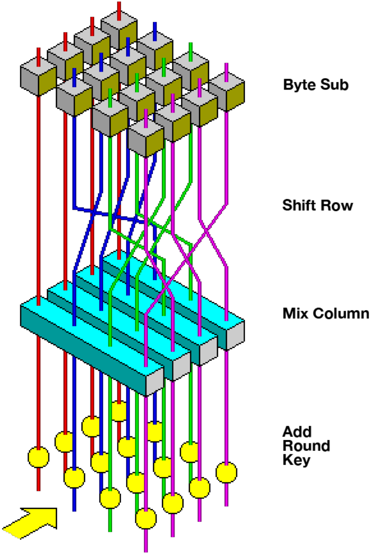
Contents

Recall: AES

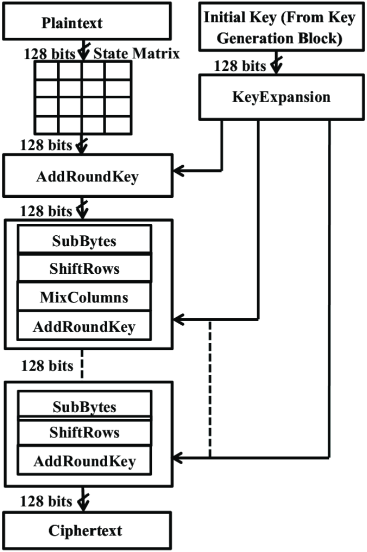
- AES is a symmetric key encryption scheme
- AES is a substitution–permutation network
- AES-128: uses 10 rounds and 128-bit keys
- Works on 4×4 column order array of 16 bytes
- Long messages are divided into 16 byte blocks
- Some modes of operations: ECB, CTR, GCM, etc.

Check out chapter 4 in Serious Cryptography by JPA.

Recall: AES



Recall: AES



Plaintext
Initial Key (From Key Generation Block)
128 bits
State Matrix
128 bits
KeyExpansion
128 bits
AddRoundKey
128 bits
SubBytes
ShiftRows
MixColumns
AddRoundKey
128 bits
SubBytes
ShiftRows
AddRoundKey
128 bits
Ciphertext

Weaknesses and Defenses

In the following slides we will look at the common ways to implement AES and its components. For each algorithm, try to point out potential information leakage and protection.

Example Code

```
def encrypt(key, plaintext):

    # AddRoundKey for initial round
    ciphertext = AddRoundKey(plaintext, key[0])

    for i in range(1, rounds):
        ciphertext = SubBytes(ciphertext)
        ciphertext = ShiftRows(ciphertext)
        ciphertext = MixColumns(ciphertext)
        ciphertext = AddRoundKey(ciphertext, key[i])

    # Final round (no MixColumns)
    ciphertext = SubBytes(ciphertext)
    ciphertext = ShiftRows(ciphertext)
    ciphertext = AddRoundKey(ciphertext, key[rounds])

    return ciphertext
```

Differential Power Analysis

Differential Power Analysis

Paul Kocher, Joshua Jaffe, and Benjamin Jun

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Abstract. Cryptosystem designers frequently assume that secrets will be manipulated in closed, reliable computing environments. Unfortunately, actual computers and microchips leak information about the operations they process. This paper examines specific methods for analyzing power consumption measurements to find secret keys from tamper resistant devices. We also discuss approaches for building cryptosystems that can operate securely in existing hardware that leaks information.

Keywords: differential power analysis, DPA, SPA, cryptanalysis, DES

Figure:
`https://paulkocher.com/doc/DifferentialPowerAnalysis.pdf2`

Simple Power Analysis (on DES)

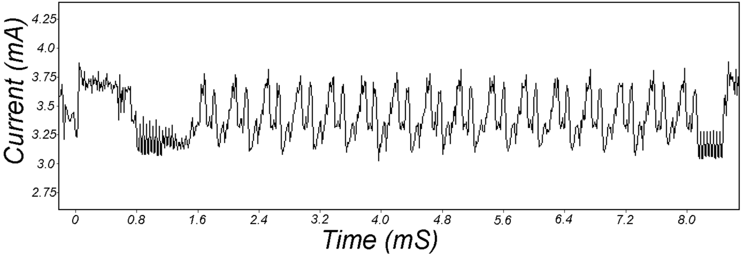


Figure 1: SPA trace showing an entire DES operation.

Detailed SPA (on DES)

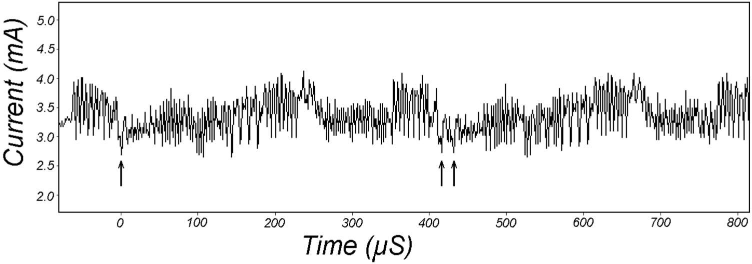


Figure 2: SPA trace showing DES rounds 2 and 3.

Correlation

Statistical Analysis via Pearson Correlation Coefficient ρ

- Linear relationship between 2 random variables (how much do they change together)
- X: predictions corresponding to one key hypothesis
- Y: measured samples corresponding to one point in time

$$\rho = \frac{\mathrm{Cov}(X, Y)}{\sqrt{\mathrm{Var}(X) \cdot \mathrm{Var}(Y)}} = \frac{\mathrm{E}[(X - \mu_X)(Y - \mu_Y)]}{\sigma_x \sigma_y}$$

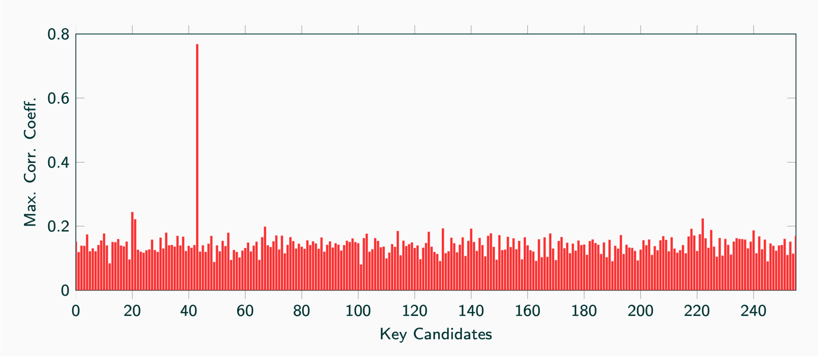
Cov = Covariance,
Var = Variance,
E = Expected value,
σ = Standard deviation,
μ = Mean

Estimate:

$$r = \frac{\sum_i (x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_i (x_i - \overline{x})^2}\sqrt{\sum_i (y_i - \overline{y})^2}}$$

$$\overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$$

Key Candidates



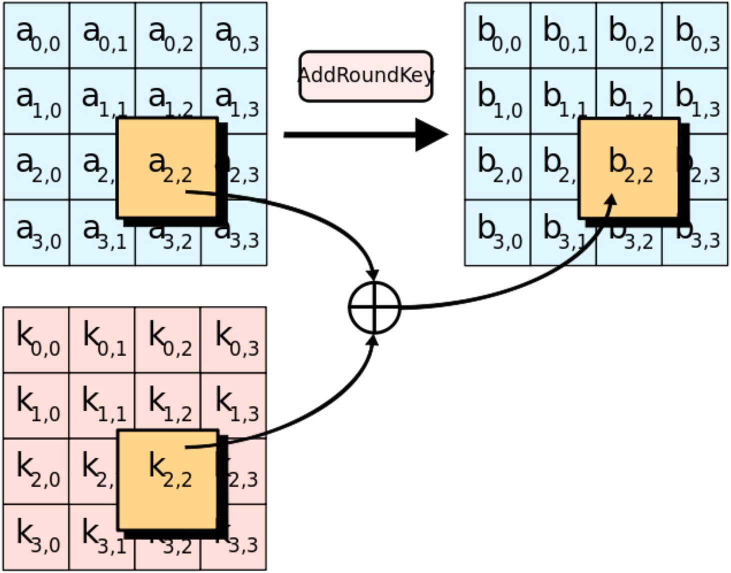
Potential Weaknesses

Some information leak directly:

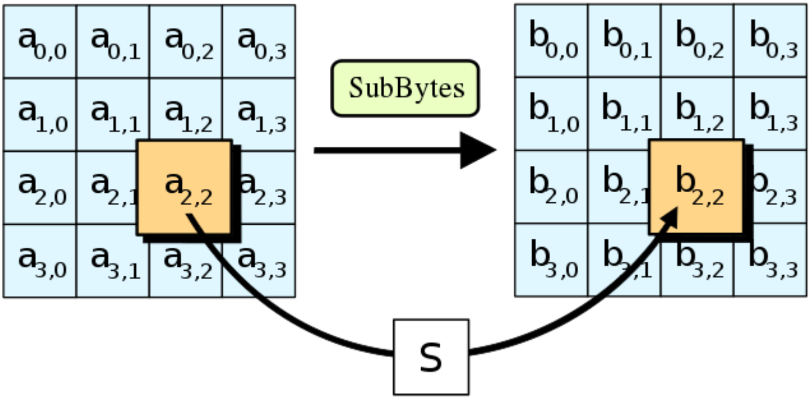
- We can easily see how many rounds are computed
- We can easily see which operation is computed
- We can compare known traces with the first round

Let us look at the underlying operations in more detail.

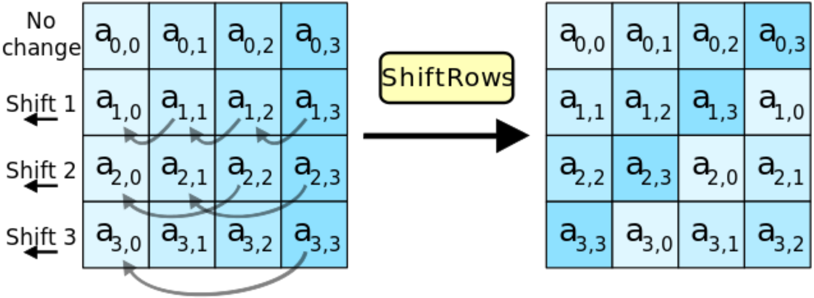
AddRoundKey



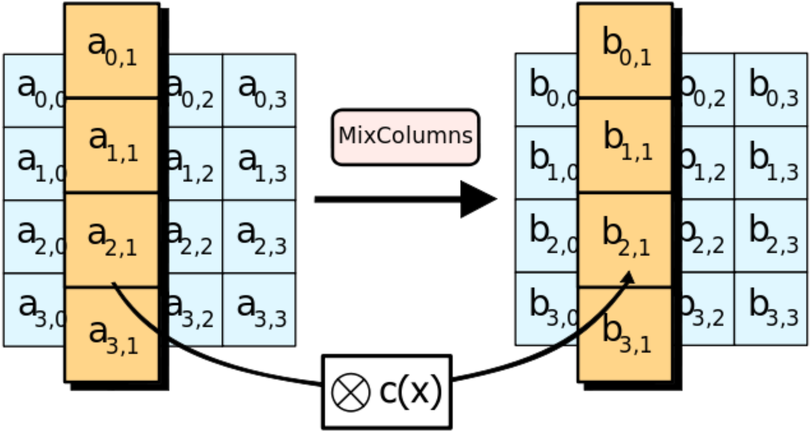
SubBytes (S-Box)



ShiftRows


No change
Shift 1
Shift 2
Shift 3
$a_{0,0}$ $a_{0,1}$ $a_{0,2}$ $a_{0,3}$
$a_{1,0}$ $a_{1,1}$ $a_{1,2}$ $a_{1,3}$
$a_{2,0}$ $a_{2,1}$ $a_{2,2}$ $a_{2,3}$
$a_{3,0}$ $a_{3,1}$ $a_{3,2}$ $a_{3,3}$
ShiftRows
$a_{0,0}$ $a_{0,1}$ $a_{0,2}$ $a_{0,3}$
$a_{1,1}$ $a_{1,2}$ $a_{1,3}$ $a_{1,0}$
$a_{2,2}$ $a_{2,3}$ $a_{2,0}$ $a_{2,1}$
$a_{3,3}$ $a_{3,0}$ $a_{3,1}$ $a_{3,2}$

MixColumns



$a_{0,1}$ $a_{0,2}$ $a_{0,3}$
$a_{1,1}$ $a_{1,2}$ $a_{1,3}$
$a_{2,1}$ $a_{2,2}$ $a_{2,3}$
$a_{3,1}$ $a_{3,2}$ $a_{3,3}$
MixColumns
$b_{0,1}$ $b_{0,3}$
$b_{1,1}$ $b_{1,3}$
$b_{2,1}$ $b_{2,3}$
$b_{3,1}$ $b_{3,3}$
$\otimes$ c(x)

Potential Weaknesses

- Computation after AddRoundKey might leak HW
- SubBytes is a non-linear operation (inverses)
- MixColumns is a polynomial/matrix multiplication
- Algebraic operations are computed over GF(2^8)

Cache-timing attacks on AES

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Potential Weaknesses

- NIST when standardizing the SubBytes in AES: “Table lookup: not vulnerable to timing attacks”
- Several finalists in the competition were secure, but Rijndael was fastest and this was important
- Flush+Reload attacks on cache leaks the secret indices of the SubBytes lookup table

Potential Defenses

We must ensure one of the following:

- Avoid memory access, or
- Always read all entries, or
- Disable cache-sharing

The latter is impractical and affects general performance.

MixColumns

```
def MixColumns(state):

    def single_col(col):

        b = (col << 1) ^ (0x11B & -(col >> 7))

        col_mixed = [
            b[0] ^ col[3] ^ col[2] ^ b[1] ^ col[1],
            b[1] ^ col[0] ^ col[3] ^ b[2] ^ col[2],
            b[2] ^ col[1] ^ col[0] ^ b[3] ^ col[3],
            b[3] ^ col[2] ^ col[1] ^ b[0] ^ col[0],
        ]
        return col_mixed

    state[:, 0] = single_col(state[:, 0])
    state[:, 1] = single_col(state[:, 1])
    state[:, 2] = single_col(state[:, 2])
    state[:, 3] = single_col(state[:, 3])
    return state
```

Sub-Algorithm

```
    def AddRoundKey(self, state, key):
        return np.bitwise_xor(state, key)

    def SubBytes(self, state):
        return self.S_box[state]

    def ShiftRows(self, state):
        return state.take(
        (0, 1, 2, 3, 5, 6, 7, 4, 10, 11, 8, 9, 15, 12, 13, 14)
        ).reshape(4, 4)
```

SubBytes (S-Box)

```
self.S_box = np.array(
    [0x63, 0x7c, 0x77, 0x7b, 0xf2, 0x6b, 0x6f, 0xc5, 0x30, 0x01, 0x67, 0x2b, 0xfe, 0xd7, 0xab, 0x76,
    0xca, 0x82, 0xc9, 0x7d, 0xfa, 0x59, 0x47, 0xf0, 0xad, 0xd4, 0xa2, 0xaf, 0x9c, 0xa4, 0x72, 0xc0,
    0xb7, 0xfd, 0x93, 0x26, 0x36, 0x3f, 0xf7, 0xcc, 0x34, 0xa5, 0xe5, 0xf1, 0x71, 0xd8, 0x31, 0x15,
    0x04, 0xc7, 0x23, 0xc3, 0x18, 0x96, 0x05, 0x9a, 0x07, 0x12, 0x80, 0xe2, 0xeb, 0x27, 0xb2, 0x75,
    0x09, 0x83, 0x2c, 0x1a, 0x1b, 0x6e, 0x5a, 0xa0, 0x52, 0x3b, 0xd6, 0xb3, 0x29, 0xe3, 0x2f, 0x84,
    0x53, 0xd1, 0x00, 0xed, 0x20, 0xfc, 0xb1, 0x5b, 0x6a, 0xcb, 0xbe, 0x39, 0x4a, 0x4c, 0x58, 0xcf,
    0xd0, 0xef, 0xaa, 0xfb, 0x43, 0x4d, 0x33, 0x85, 0x45, 0xf9, 0x02, 0x7f, 0x50, 0x3c, 0x9f, 0xa8,
    0x51, 0xa3, 0x40, 0x8f, 0x92, 0x9d, 0x38, 0xf5, 0xbc, 0xb6, 0xda, 0x21, 0x10, 0xff, 0xf3, 0xd2,
    0xcd, 0x0c, 0x13, 0xec, 0x5f, 0x97, 0x44, 0x17, 0xc4, 0xa7, 0x7e, 0x3d, 0x64, 0x5d, 0x19, 0x73,
    0x60, 0x81, 0x4f, 0xdc, 0x22, 0x2a, 0x90, 0x88, 0x46, 0xee, 0xb8, 0x14, 0xde, 0x5e, 0x0b, 0xdb,
    0xe0, 0x32, 0x3a, 0x0a, 0x49, 0x06, 0x24, 0x5c, 0xc2, 0xd3, 0xac, 0x62, 0x91, 0x95, 0xe4, 0x79,
    0xe7, 0xc8, 0x37, 0x6d, 0x8d, 0xd5, 0x4e, 0xa9, 0x6c, 0x56, 0xf4, 0xea, 0x65, 0x7a, 0xae, 0x08,
    0xba, 0x78, 0x25, 0x2e, 0x1c, 0xa6, 0xb4, 0xc6, 0xe8, 0xdd, 0x74, 0x1f, 0x4b, 0xbd, 0x8b, 0x8a,
    0x70, 0x3e, 0xb5, 0x66, 0x48, 0x03, 0xf6, 0x0e, 0x61, 0x35, 0x57, 0xb9, 0x86, 0xc1, 0x1d, 0x9e,
    0xe1, 0xf8, 0x98, 0x11, 0x69, 0xd9, 0x8e, 0x94, 0x9b, 0x1e, 0x87, 0xe9, 0xce, 0x55, 0x28, 0xdf,
    0x8c, 0xa1, 0x89, 0x0d, 0xbf, 0xe6, 0x42, 0x68, 0x41, 0x99, 0x2d, 0x0f, 0xb0, 0x54, 0xbb, 0x16], np.uint8)
```

Bitslicing

A Fast New DES Implementation in Software

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Bitslicing

Technique to avoid side-channel analysis:

- Work over bits not bytes in GF(2^8)
- Only use OR, AND, XOR, NAND, etc.
- Execute operations on vectors
- Is slower, but constant time
- Need a circuit for table lookup
- Integrated in hardware AES

We can combine this with randomized masking.

Masking

Provably Secure Higher-Order Masking of AES⋆

Matthieu Rivain[1] and Emmanuel Prouff[2]

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[2] Oberthur Technologies
e.prouff@oberthur.com

Figure: https://eprint.iacr.org/2010/441.pdf

AES Masking

- d-order masking: split secret in d parts
- linear operations are easy, non-linear not
- AddKey, ShiftRows and MixColumns are linear
- SubBytes is not linear: requires extra work
- statistical analysis is exponential in d
- added work scales with $d \log_2 d$ operations

Masking AND

Secure logical AND. Let a an b be two bits and let c denote $\mathrm{AND}(a,b) = ab$. Let us assume that a and b have been respectively split into $d+1$ shares $(a_i)_{0\leqslant i\leqslant d}$ and $(b_i)_{0\leqslant i\leqslant d}$ such that $\bigoplus_i a_i = a$ and $\bigoplus_i b_i = b$. To securely compute a $(d+1)$-tuple $(c_i)_{0\leqslant i\leqslant d}$ s.t. $\bigoplus_i c_i = c$, Ishai *et al.* perform the following steps:

1. For every $0 \leqslant i < j \leqslant d$, pick up a random bit $r_{i,j}$.
2. For every $0 \leqslant i < j \leqslant d$, compute $r_{j,i} = (r_{i,j} \oplus a_i b_j) \oplus a_j b_i$.
3. For every $0 \leqslant i \leqslant d$, compute $c_i = a_i b_i \oplus \bigoplus_{j\neq i} r_{i,j}$.

Masking AND

The completeness of the solution follows from:

$$\bigoplus_i c_i = \bigoplus_i \big(a_i b_i \oplus \bigoplus_{j \neq i} r_{i,j}\big) = \bigoplus_i \big(a_i b_i \oplus \bigoplus_{j>i} r_{i,j} \oplus \bigoplus_{j<i} (r_{j,i} \oplus a_i b_j \oplus a_j b_i)\big)$$

$$= \bigoplus_i \big(a_i b_i \oplus \bigoplus_{j<i} (a_i b_j \oplus a_j b_i)\big) = \big(\bigoplus_i a_i\big)\big(\bigoplus_i b_i\big) \quad .$$

Timings

Table 2. Comparison of secure AES implementations

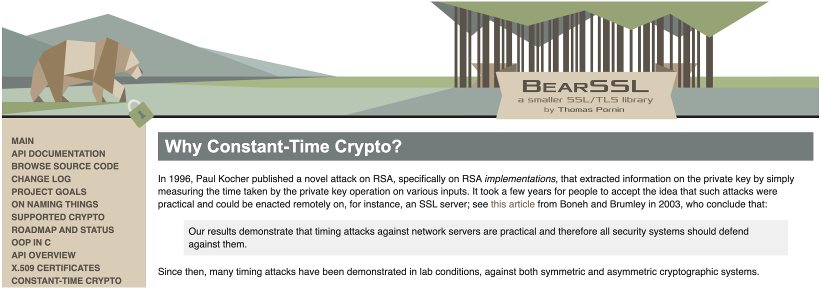
Method	Reference	cycles	RAM (bytes)	ROM (bytes)
Unprotected Implementation				
No Masking	Na.	3×10^3	32	1150
First Order Masking				
Re-computation	[23]	10×10^3	$256 + 35$	1553
Tower Field in $\mathbb{F}_4$	[28, 29]	77×10^3	42	3195
Our scheme for $d = 1$	This paper	129×10^3	73	3153
Second Order Masking				
Double Re-computations	[38]	594×10^3	$512 + 90$	2336
Single Re-computation	[34]	672×10^3	$256 + 86$	2215
Our scheme for $d = 2$	This paper	271×10^3	79	3845
Third Order Masking				
Our scheme for $d = 3$	This paper	470×10^3	103	4648

Summary

Protecting secret key computations are difficult. We need to:

- avoid lookup tables
- constant time operations
- vectorize operations
- use randomness/masking

Bear SSL



MAIN
API DOCUMENTATION
BROWSE SOURCE CODE
CHANGE LOG
PROJECT GOALS
ON NAMING THINGS
SUPPORTED CRYPTO
ROADMAP AND STATUS
OOP IN C
API OVERVIEW
X.509 CERTIFICATES
CONSTANT-TIME CRYPTO

Why Constant-Time Crypto?

In 1996, Paul Kocher published a novel attack on RSA, specifically on RSA *implementations*, that extracted information on the private key by simply measuring the time taken by the private key operation on various inputs. It took a few years for people to accept the idea that such attacks were practical and could be enacted remotely on, for instance, an SSL server; see this article from Boneh and Brumley in 2003, who conclude that:

> Our results demonstrate that timing attacks against network servers are practical and therefore all security systems should defend against them.

Since then, many timing attacks have been demonstrated in lab conditions, against both symmetric and asymmetric cryptographic systems.

Figure: `https://www.bearssl.org/constanttime.html#aes`

Questions?