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Efficient Leak Resistant Modular Exponentiation in RNS

Andrea Lesavourey⁽¹⁾, **Christophe Negre**⁽¹⁾ and Thomas Plantard⁽²⁾

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24-th Symposium on Computer Arithmetic,
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Outline

1 Cryptography

- RSA cryptosystem
- Power analysis
- Montgomery multiplication in RNS

2 Randomized modular exponentiation in RNS

- Randomized Montgomery multiplication
- Proposed approach
- Level of randomization

3 Conclusion

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1 Cryptography

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3 Conclusion

RSA encryption (Rivest, Shamir and Adleman)

Bob chooses p and q two large prime numbers and computes $N = pq$. He generates E and D two integers such that $ED = 1 \pmod{(p-1)(q-1)}$.

- **Public Key:** N, D .
- **Private Key:** E, p, q .
- Alice encrypts a message m by: $c = m^D \pmod N$.
- Bob decrypts c by doing: $c^E = m^{ED} \pmod N = m$.

An algorithm for modular exponentiation : Right-to-left Square-and-multiply

Require: A modulus N , an integer $X \in [0, N[$ and an exponent

$$E = (e_{\ell-1}, \dots, e_0)_2$$

Ensure: $R = X^E \pmod{N}$

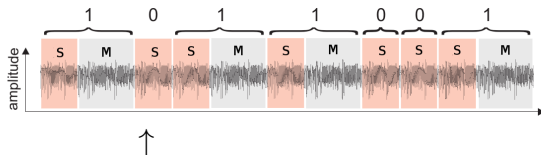
```
1:  $R \leftarrow 1$ 
2:  $Z \leftarrow X$ 
3: for  $i$  from 0 to  $\ell - 1$ 
   do
4:   if  $e_i = 1$  then
5:      $R \leftarrow R \times Z \pmod{N}$ 
6:   end if
7:    $Z \leftarrow Z^2 \pmod{N}$ 
8: end for
9: return  $R$ 
```

$$X^E = X^{\sum_{i=0}^{\ell-1} e_i 2^i}$$

$$X^E = X^{e_{\ell-1} 2^{\ell-1}} \times \dots \times X^{e_1 2^1} \times X^{e_0 2^0}$$

Simple power analysis

$E = (e_\ell, \dots, e_0)_2$ and $X \in [0, N[$



Square-and-multiply

$R \leftarrow 1$

$Z \leftarrow X$

for $i = 0$ **to** $\ell - 1$ **do**

if $e_i = 1$ **then**

$R \leftarrow R \cdot Z \pmod N$

endif

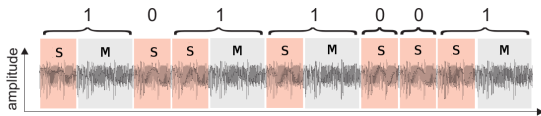
$Z \leftarrow Z^2 \pmod N$

endfor

return(R)

Simple power analysis

$$E = (e_\ell, \dots, e_0)_2 \text{ and } X \in [0, N[$$



```

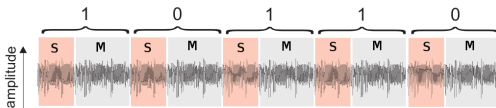
Square-and-multiply
R ← 1
Z ← X
for i = 0 to ℓ - 1 do
  if ei = 1 then
    R ← R · Z mod N
  endif
  Z ← Z2 mod N
endfor
return(R)
    
```

```

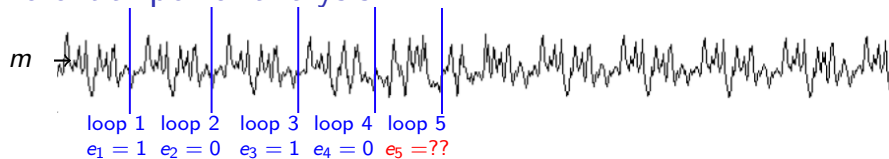
Square-and-multiply-always
R0 ← 1
R1 ← 1
Z ← X
for i = 0 to ℓ - 1 do
  if ei = 0 then
    R0 ← R0 · Z mod N
  else
    R1 ← R1 · Z mod N
  endif
endfor
Z ← Z2 mod N
return(R1)
    
```

```

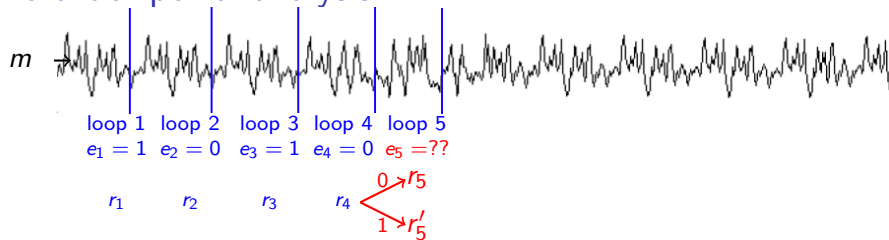
Montgomery-ladder
R ← 1
R' ← X
for i = ℓ to 1 do
  if ki = 1 then
    R ← R · R' mod N
    R' ← R'2 mod N
  else
    R' ← R · R' mod N
    R ← R2
  endif
endfor
return(R)
    
```



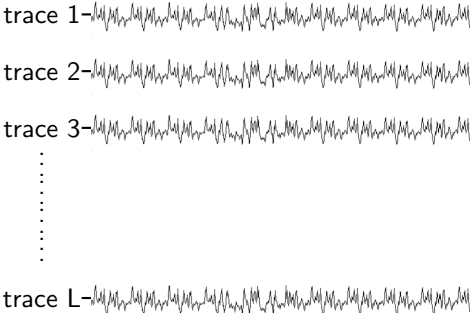
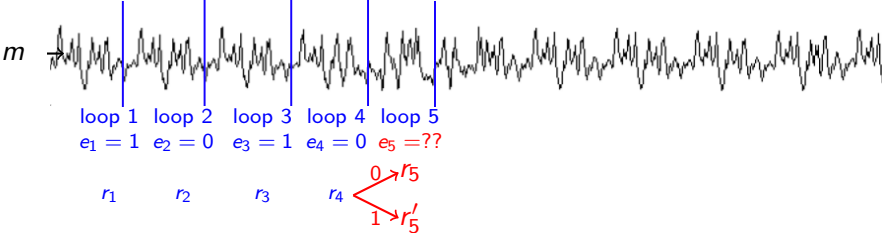
Differential power analysis



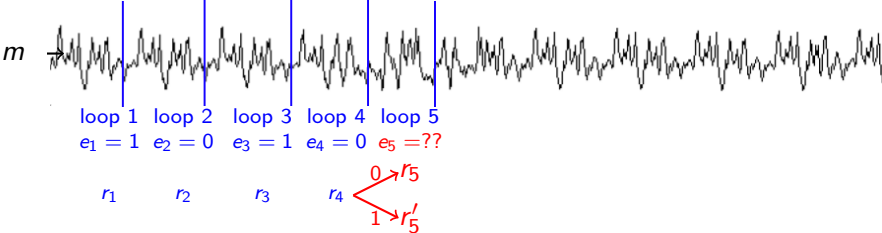
Differential power analysis



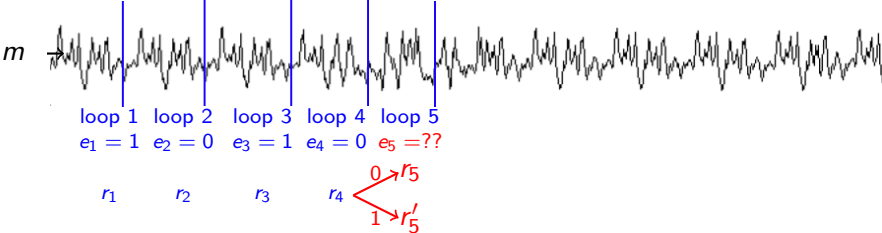
Differential power analysis



Differential power analysis



Differential power analysis



Counter-measure: Randomization of the exponent and data.

Montgomery multiplication

Basic modular multiplication. For $X, Y \in [0, N[$

- 1 Product. $Z \leftarrow X \times Y$
- 2 Reduction. $Q \leftarrow \lfloor Z/N \rfloor$ and $R \leftarrow Z - Q \times N$

Montgomery multiplication

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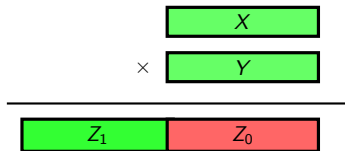
Require: $X, Y \in [0, N[$ and
 $A = 2^n > N$

Ensure: $R = X \times Y \times A^{-1} \pmod{N}$

1: $Z \leftarrow X \times Y$

2: $Q \leftarrow N^{-1} \times Z \pmod{A}$

3: $R \leftarrow (Z - Q \times N)/A$



Montgomery multiplication

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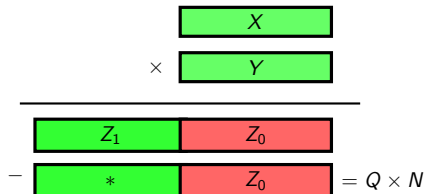
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Montgomery Multiplication

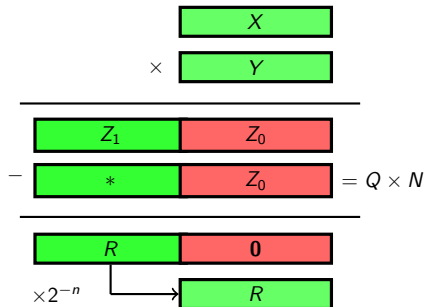
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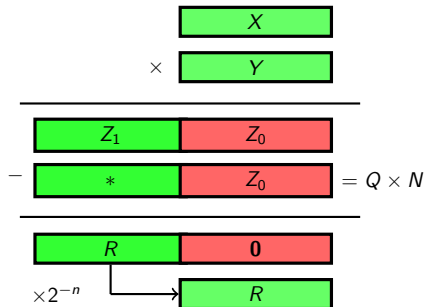
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3: $R \leftarrow (Z - Q \times N)/A$



Montgomery representation.

- 1 $\tilde{X} = XA \pmod{N}$ provides
- 2 $MontMul(\tilde{X}, \tilde{Y}) = (XA) \times (YA) \times A^{-1} \pmod{N} = XYA \pmod{N}$

Montgomery multiplication in residue number system

- Let $\mathcal{A} = \{a_1, \dots, a_t\}$ be a set t co-prime integers.

Montgomery multiplication in residue number system

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$$[X]_{\mathcal{A}} = (x_1 = X \pmod{a_1}, \dots, x_t = X \pmod{a_t}).$$

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- The Chinese remainder theorem tell us that for $\text{op} \in \{+, \times\}$

$$[X]_{\mathcal{A}} \text{ op } [Y]_{\mathcal{A}} = ([x_1 \text{ op } y_1]_{a_1}, \dots, [x_t \text{ op } y_t]_{a_t}) \Leftrightarrow X \text{ op } Y \pmod{A}$$

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Montgomery Multiplication in RNS

Require: X, Y in $\mathcal{A} \cup \mathcal{B}$

Ensure: $XYA^{-1} \pmod{N}$ in $\mathcal{A} \cup \mathcal{B}$

1: $[Q]_{\mathcal{A}} \leftarrow [XYN^{-1}]_{\mathcal{A}}$

3: $[Z]_{\mathcal{B}} \leftarrow [(XY - QN)A^{-1}]_{\mathcal{B}}$

5: **return** $(Z_{\mathcal{A} \cup \mathcal{B}})$

Montgomery multiplication in residue number system

- Let $\mathcal{A} = \{a_1, \dots, a_t\}$ be a set t co-prime integers.
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- 1: $[Q]_{\mathcal{A}} \leftarrow [XYN^{-1}]_{\mathcal{A}}$
- 2: $[Q]_{\mathcal{B}} \leftarrow BE_{\mathcal{A} \rightarrow \mathcal{B}}([Q]_{\mathcal{A}})$
- 3: $[Z]_{\mathcal{B}} \leftarrow [(XY - QN)A^{-1}]_{\mathcal{B}}$
- 4: $[Z]_{\mathcal{A}} \leftarrow BE_{\mathcal{B} \rightarrow \mathcal{A}}([Z]_{\mathcal{B}})$
- 5: **return** $(Z_{\mathcal{A} \cup \mathcal{B}})$

Outline

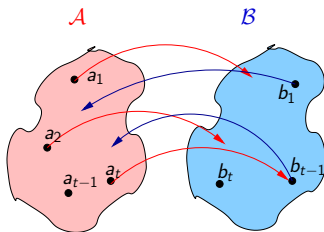
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Randomization in RNS (LRA CHES 2004)

We have

$$\tilde{X}_{old} = [XA_{old}]_{\mathcal{A}_{old} \cup \mathcal{B}_{old}}$$

we permute the basis elements $\mathcal{A}_{old} \cup \mathcal{B}_{old} \rightarrow \mathcal{A}_{new} \cup \mathcal{B}_{new}$



this leads to a new representation of X

$$\tilde{X}_{new} = [XA_{new}]_{\mathcal{A}_{new} \cup \mathcal{B}_{new}}$$

Cost

Two Montgomery multiplications :

$$XA_{old} \bmod N \rightarrow XA_{old}A_{new} \bmod N \rightarrow XA_{new} \bmod N.$$

Randomized square-and-multiply-always

- Input: N , $X \in [0, N[$, $E = (e_{\ell-1}, \dots, e_0)_2$ and $\mathcal{M} = \{m_1, \dots, m_{2t}\}$.
- Output: $X^E \pmod N$

Square-and-mult-always

```
 $\mathcal{A}, \mathcal{B} \leftarrow \text{random split } \mathcal{M}$   
 $\tilde{Z} \leftarrow [X]_{\mathcal{A} \cup \mathcal{B}},$   
 $\tilde{R}_0 \leftarrow [1]_{\mathcal{A} \cup \mathcal{B}}, \tilde{R}_1 \leftarrow [1]_{\mathcal{A} \cup \mathcal{B}}$   
for  $i$  from 0 to  $\ell - 1$  do  
     $\tilde{R}_{e_i} \leftarrow \text{MM\_RNS}(\tilde{R}_{e_i}, \tilde{Z}, \mathcal{A}, \mathcal{B})$   
     $\tilde{Z} \leftarrow \text{MM\_RNS}(\tilde{Z}, \tilde{Z}, \mathcal{A}, \mathcal{B})$   
end for  
return  $\tilde{R}_1$ 
```

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   $\tilde{Z} \leftarrow \text{MM\_RNS}(\tilde{Z}, \tilde{Z}, \mathcal{A}, \mathcal{B})$   
   $\text{Randomise}(\mathcal{A}_{old}, \mathcal{B}_{old}, \mathcal{A}, \mathcal{B})$   
   $\tilde{Z} \leftarrow \text{Update}(\tilde{Z}, \mathcal{A}_{old}, \mathcal{B}_{old}, \mathcal{A}, \mathcal{B})$   
   $\tilde{R}_0 \leftarrow \text{Update}(\tilde{R}_0, \mathcal{A}_{old}, \mathcal{B}_{old}, \mathcal{A}, \mathcal{B})$   
   $\tilde{R}_1 \leftarrow \text{Update}(\tilde{R}_1, \mathcal{A}_{old}, \mathcal{B}_{old}, \mathcal{A}, \mathcal{B})$   
end for  
return  $\tilde{R}_1$ 
```

Randomized square-and-multiply-always

- Input: N , $X \in [0, N[$, $E = (e_{\ell-1}, \dots, e_0)_2$ and $\mathcal{M} = \{m_1, \dots, m_{2t}\}$.
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Randomized Square-and-mult-always

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   $\text{Randomise}(\mathcal{A}_{old}, \mathcal{B}_{old}, \mathcal{A}, \mathcal{B})$   
   $\tilde{Z} \leftarrow \text{Update}(\tilde{Z}, \mathcal{A}_{old}, \mathcal{B}_{old}, \mathcal{A}, \mathcal{B})$   
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end for  
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```

Randomized square-and-multiply-always

- Input: N , $X \in [0, N[$, $E = (e_{\ell-1}, \dots, e_0)_2$ and $\mathcal{M} = \{m_1, \dots, m_{2t}\}$.
- Output: $X^E \bmod N$

Randomized Square-and-mult-always

```
 $\mathcal{A}, \mathcal{B} \leftarrow \text{random split } \mathcal{M}$   
 $\tilde{Z} \leftarrow [\tilde{X}]_{\mathcal{AUB}}$ ,  
 $\tilde{R}_0 \leftarrow [\tilde{1}]_{\mathcal{AUB}}$ ,  $\tilde{R}_1 \leftarrow [\tilde{1}]_{\mathcal{AUB}}$   
for  $i$  from 0 to  $\ell - 1$  do  
   $\tilde{R}_{e_i} \leftarrow \text{MM\_RNS}(\tilde{R}_{e_i}, \tilde{Z}, \mathcal{A}, \mathcal{B})$   
   $\tilde{Z} \leftarrow \text{MM\_RNS}(\tilde{Z}, \tilde{Z}, \mathcal{A}, \mathcal{B})$   
  Randomise( $\mathcal{A}_{old}, \mathcal{B}_{old}, \mathcal{A}, \mathcal{B}$ )  
   $\tilde{Z} \leftarrow \text{Update}(\tilde{Z}, \mathcal{A}_{old}, \mathcal{B}_{old}, \mathcal{A}, \mathcal{B})$   
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end for  
return  $\tilde{R}_1$ 
```

Proposed

```
 $\mathcal{A}, \mathcal{B} \leftarrow \text{random split } \mathcal{M}$   
 $\tilde{Z} \leftarrow [\tilde{X}]_{\mathcal{AUB}}$ ,  
 $\tilde{R}_0 \leftarrow [\tilde{1}]_{\mathcal{AUB}}$ ,  $\tilde{R}_1 \leftarrow [\tilde{1}]_{\mathcal{AUB}}$   
for  $i$  from 0 to  $\ell - 1$  do  
   $\mathcal{A}'_{e_i}, \mathcal{B}'_{e_i} \leftarrow \text{random split } \mathcal{M}$   
   $\tilde{R}_{e_i} \leftarrow \text{MM\_RNS}(\tilde{R}_{e_i}, \tilde{Z}, \mathcal{A}'_{e_i}, \mathcal{B}'_{e_i})$   
   $\tilde{Z} \leftarrow \text{MM\_RNS}(\tilde{Z}, \tilde{Z}, \mathcal{A}, \mathcal{B})$   
  Randomise( $\mathcal{A}_{old}, \mathcal{B}_{old}, \mathcal{A}, \mathcal{B}$ )  
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Example

For $E = 7 = (111)_2$ and $\mathcal{M} = \{m_1, m_2, m_3, m_4\}$

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- Initialization: $\mathcal{A} = \{m_1, m_2\}, \mathcal{B} = \{m_3, m_4\}$ leads to

$$R_1 = m_1 m_2 \pmod{N}$$

$$Z = X m_1 m_2 \pmod{N}$$

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$$\begin{aligned}R_1 &= m_1 m_2 \pmod{N} \\ Z &= X m_1 m_2 \pmod{N}\end{aligned}$$

- Loop 1: $\mathcal{A}_1 = \{m_2, m_4\}, \mathcal{B}_1 = \{m_1, m_3\}$ we get

$$R_1 = (m_1 m_2) \times \underbrace{(X m_1 m_2)}_Z \times \underbrace{(m_2^{-1} m_4^{-1})}_{\text{Mont. factor}} = X m_1^2 m_2 m_4^{-1}$$

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$\mathcal{A} = \{m_1, m_3\}, \mathcal{B} = \{m_2, m_4\}$ leads to

$$Z = X^2 m_1 m_3$$

- **Loop 2:** $\mathcal{A}_1 = \{m_1, m_4\}, \mathcal{B}_1 = \{m_2, m_3\}$ we get

$$R_1 = X m_1^2 m_2 m_4^{-1} \times (X^2 m_1 m_3) \times (m_1^{-1} m_4^{-1}) = X^3 m_1^2 m_2 m_3 m_4^{-2}$$

Example

For $E = 7 = (111)_2$ and $\mathcal{M} = \{m_1, m_2, m_3, m_4\}$

- **Initialization:** $\mathcal{A} = \{m_1, m_2\}, \mathcal{B} = \{m_3, m_4\}$ leads to

$$\begin{aligned}R_1 &= m_1 m_2 \pmod{N} \\Z &= X m_1 m_2 \pmod{N}\end{aligned}$$

- **Loop 1:** $\mathcal{A}_1 = \{m_2, m_4\}, \mathcal{B}_1 = \{m_1, m_3\}$ we get

$$R_1 = (m_1 m_2) \times \underbrace{(X m_1 m_2)}_Z \times \underbrace{(m_2^{-1} m_4^{-1})}_{\text{Mont. factor}} = X m_1^2 m_2 m_4^{-1}$$

$\mathcal{A} = \{m_1, m_3\}, \mathcal{B} = \{m_2, m_4\}$ leads to

$$Z = X^2 m_1 m_3$$

- **Loop 2:** $\mathcal{A}_1 = \{m_1, m_4\}, \mathcal{B}_1 = \{m_2, m_3\}$ we get

$$R_1 = X m_1^2 m_2 m_4^{-1} \times (X^2 m_1 m_3) \times (m_1^{-1} m_4^{-1}) = X^3 m_1^2 m_2 m_3 m_4^{-2}$$

- Etc.

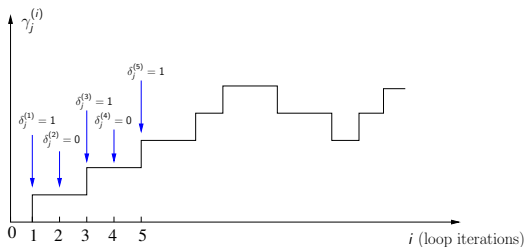
Random evolution of the mask

After i loop iterations we have

$$\tilde{R}_1^{(i)} = \mathcal{X}^{\sum_{j=0}^{i-1} e_j 2^j} \times \prod_{j=0}^{2t} m_j^{\gamma_j^{(i)}} \pmod N$$

and each $\gamma_j^{(i)}$ evolves randomly as

$$\gamma_j^{(i+1)} = \gamma_j^{(i)} + \delta_j^{(i)} \text{ with } \delta_j^{(i)} \in \{-1, 0, 1\} \text{ and } \begin{cases} \mathbb{P}(\delta_j^{(i)} = 1) = 1/8, \\ \mathbb{P}(\delta_j^{(i)} = -1) = 1/8, \\ \mathbb{P}(\delta_j^{(i)} = 0) = 3/4. \end{cases}$$



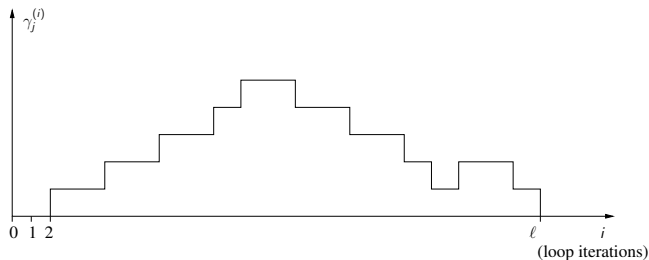
Removing the final mask

Problem: at the end we have to remove the final mask $\prod_{j=1}^{2t} m_j^{\gamma_j^{(\ell)}}$ from

$$\tilde{X} = X^E \cdot \prod_{j=1}^{2t} m_j^{\gamma_j^{(\ell)}} \pmod{N}.$$

Strategy: we force $\gamma_j^{(\ell)}$ to be equal 0 as follows

- During the first half of the iterations each $\gamma_j^{(i)}$ evolves freely.
- During the second half we constrain each $|\gamma_j^{(i)}|$ to decrease toward 0.



Level of randomization

- The probabilities of the mask exponents satisfy

$$\begin{aligned}\mathbb{P}(\gamma_j^{(i)} = d) &= \sum_{k=d}^{d+\lfloor (i-d)/2 \rfloor} \binom{i}{k} \binom{i-k}{k-d} \left(\frac{1}{8}\right)^{2k-d} \left(\frac{3}{4}\right)^{i-2k+d} \\ \mathbb{P}(\Gamma^{(i)} = \Gamma) &\leq \prod_{j=1}^t \mathbb{P}(\gamma_j^{(i)} = \gamma_j) \leq \prod_{j=1}^t \mathbb{P}(\gamma_j^{(i)} = 0)\end{aligned}$$

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- **Comparison:** for a 2048-bit RSA modulus and $t = 32$:

- ▶ CHES 04:

- ★ Montgomery-ladder,
- ★ 4MM_RNS per randomization,
- ★ all masks are controlled.

- ▶ Proposed:

- ★ right-left square-and-multiply-always,
- ★ 2MM_RNS per randomization
- ★ the masks for R_0 and R_1 are not controlled.

Approach	loop 1	loop 5	loop 10	loop 50	loop 100
CHES 04	$4.17 \cdot 10^{-38}$	$4.17 \cdot 10^{-38}$	$4.17 \cdot 10^{-38}$	$4.17 \cdot 10^{-38}$	$4.17 \cdot 10^{-38}$
Proposed	10^{-8}	$5 \cdot 10^{-28}$	$1.7 \cdot 10^{-38}$	$2.69 \cdot 10^{-61}$	$5.75 \cdot 10^{-71}$

Outline

- 1 Cryptography
 - RSA cryptosystem
 - Power analysis
 - Montgomery multiplication in RNS
- 2 Randomized modular exponentiation in RNS
 - Randomized Montgomery multiplication
 - Proposed approach
 - Level of randomization
- 3 Conclusion

Conclusion

Secure embedded implementation of RSA:

- Randomized modular exponentiation
- But leak resistant arithmetic (CHES 04) is costly: 4 MM_RNS per randomization

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We proposed:

- To apply LRA to right-to-left exponentiation.
- Avoid some correction of Montgomery Factor.
- This decreases the computational cost: 2 MM_RNS per randomization.
- Increases the level of randomization after a small number of loop.

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Secure embedded implementation of RSA:

- Randomized modular exponentiation
- But leak resistant arithmetic (CHES 04) is costly: 4 MM_RNS per randomization

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- To apply LRA to right-to-left exponentiation.
- Avoid some correction of Montgomery Factor.
- This decreases the computational cost: 2 MM_RNS per randomization.
- Increases the level of randomization after a small number of loop.

Perspectives:

- A better estimation of the level of randomization.
- Is it a good counter-measure against horizontal power analysis ?

Thank you for your attention!